# The Effects of Timber Harvesting and Windthrow on Landslide Initiation, Southwestern Vancouver Island

by

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**Degree:** **Master of Science**

**Title of Thesis:** **The Effects of Timber Harvesting and Windthrow on Landslide Initiation, Southwestern Vancouver Island**

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# Abstract

A severe storm in November 2006 caused over 200 landslides on southwestern Vancouver Island. This thesis investigates 48 field truthed landslides and 233 GIS mapped landslides in unlogged and logged terrain. The impact of windthrow, clearcutting, soil properties and root reinforcement on landslide initiation were analysed within eight months after the storm event. The windthrow landslide density was 25 and 123 times the clearcut and natural landslide densities, respectively. Windthrow related landslides were concentrated on south to east aspects, near clearcut boundaries and recent clearcuts (<10 years old). Windthrow landslides occur on steeper, convex, well drained, colluvial slopes with thinner soils than clearcut landslides.

This study used a root density and quality approach to define the loss of root reinforcement after logging. The results show a rapid decline over the first 11 years followed by an increase up to 50 years. Root quality shows a similar trend after logging.

**Keywords:** Landslides and debris flows; Windthrow; Clearcuts; Organic soil; Root reinforcement, density, and decay; Vancouver Island

# Dedication

I dedicate this thesis to my mother, Anna Marie McDonald (1946 – 2010). My mother and I loved nature and we enjoyed hiking and experiencing nature together. I loved sharing my stories of my thesis research and my work with her. She would have loved to see the completion of my thesis and my graduation.

**I Love You Mom "Jeg Elsker Dig Mor"**

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My gratitude is also extended to my field assistants, Jen Owen and Melissa Dinsdale whose hard work and long traverses in steep, wet, brushy terrain made this thesis possible.

A very special thanks goes to Dave van Zeyl who helped me tremendously with the GIS analysis and was there for me whenever I called upon him. I would also like to thank Dave Sacco and James Newby who also assisted me with the GIS analysis. Without their GIS assistance there would be no windthrow chapter.

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# 1: Introduction

## 1.1 Context

The west coast of Vancouver Island is a land mass with high precipitation, extreme winds, old growth and second growth forests, extensive river systems, and steep glaciated terrain. Industries such as forestry, fishing, mining, and recreation are all dependent upon these resources. Therefore, it is crucial for geoscientists, engineers, and foresters to understand the effects that these variables have on one another. Logging has been occurring on steeper and less stable terrain where there are increased landslide hazards. The soil and terrain attributes contributing to landslide initiation have been the subject of several terrain attribute and landslide case studies over the past 20 years (Rollerson et al., 1998, 2002; Jakob, 2000; Wolter et al., 2010). The higher frequency of landslides within the first 15 years after logging was investigated by O'Loughlin (1974a) in the Coast Mountains near Vancouver, British Columbia. A loss of root strength was associated with the increase in landslide frequency. Since the early 1970's limited research has been conducted investigating the role of root reinforcement on coastal BC.

The impact of precipitation on slope stability on coastal BC and Vancouver Island has been evaluated in numerous studies including Church and Miles, (1987); Marquis, (2001); Jakob and Weatherly, (2003); Miles et al., (2008) and Guthrie et al., (2010). Guthrie et al. (2010) found that high precipitation storm events are becoming more frequent and can lead to conditions capable of initiating landslides. Clearcutting and its effects on windthrow (Rollerson et al., 2009) in conjunction with weather were investigated on Vancouver Island (Mitchell et al., 2001, 2008). These studies analysed the impact of windthrow along cutblock edges and forests on a landscape level.

The role of decaying roots and the resulting organic rich basal layer was examined by researchers for its chemical and physical properties on forest soils (Sanborn and Lavkulich, 1989a; Martin and Lowe, 1989). Research on how decaying roots affect the geotechnical properties of the organic layer and groundwater flow and their impact on slope stability is limited.

A gap in knowledge exists on Vancouver Island regarding the importance of plant roots in conjunction with terrain and soil attributes, climate, and human influences (eg. logging, roads, and mining). This research project will address the gap in knowledge which exists in the field of forest geoscience.

## 1.2 Project Background

A large precipitation and windstorm event between November 12 and 17, 2006 impacted southwestern Vancouver Island and initiated over 230 landslides. A storm of this magnitude initiating a large number of landslides over a limited geographical area was an excellent opportunity to examine the effects of root reinforcement and windthrow on slope stability. The possibility of researching landslides after the early winter storms in 2006 was discussed in January 2007. Initially the objectives of this thesis focussed on researching the role of root reinforcement after logging and investigating the geotechnical properties of a basal organic layer observed at landslide locations on coastal BC. The objectives of the research were presented in the thesis colloquium in May 2007.

Field data collection commenced in late May 2007 based from the Marine Science Centre in Bamfield, BC on southwestern Vancouver Island. Landslide reports completed by Western Forest Products were acquired from the Ministry of Forests district office in Port Alberni. Landslide maps were obtained from Western Forest Products before starting the field work. No pre-storm satellite imagery was available in summer 2007, only pre-storm aerial photos and orthophotos were obtained. Consequently, a majority of the landslide identification was dependent on truck and helicopter reconnaissance completed by Western Forest Products immediately after the storms events. Within the first three days of data collection, another branch of the research started to evolve. Initially, only landslide and root data from open slope clearcut landslides was collected. However, a large number of landslides were identified in windthrow patches adjacent to clearcuts. It was decided at that time to include open slope windthrow landslides in the field data collection. Data collection was carried out on windthrow and clearcut associated landslides in the same manner to avoid bias in the sampling procedure.

Near the end of the field research in July 2007, the author of this thesis met with Dr. Steve Mitchell and Dr. Rick Guthrie about the possibility of researching the effects of windthrow on landslide initiation. In January 2008, my thesis committee met with Dr. Mitchell to discuss the possibility of researching the effects of windthrow on landslide initiation. Dr. Mitchell provided forest cover information within the project area for Tree Farm Licence (TFL) 44. Dr. Guthrie provided SPOT satellite imagery (2.5 m resolution) from summer 2007 and GIS shape files. The shape files included landslides, windthrow patches, clearcuts and roads that were identified by Caslys Consulting during the change detection analysis. Landslides and windthrow patches were added, by the author of this thesis, to the shape files by using the SPOT 2007 satellite imagery in conjunction with field truthing from the summer 2007. Errors were immediately observed in the MOE shape files with respect to the identification of windthrow patches and clearcuts, as well as the identification of landslides. Several windthrow patches were identified as clearcuts and a number of landslides were not identified in clearcuts or windthrow areas.

Further checking of windthrow patches was conducted by using Western Forest Products orthophoto imagery (0.3 m resolution) from June 2007. Several hundred patches of windthrow and about one hundred landslides were identified, in addition to the change detection, with the higher resolution orthophoto imagery.

Mapping of windthrow and landslides was completed by the author of this thesis. Dave van Zeyl conducted the GIS analysis by processing elevation models and extracting relevant data from the windthrow, landslide and clearcut polygons. Several people and organizations were involved in contributing to this thesis project and their contributions are appreciated.

## 1.3 Research Objectives

The role of roots in soil reinforcement and soil protection, wind support, hydrology and soil mechanics requires investigation in order to understand slope stability in forested terrain. A knowledge gap exists with respect to trees and their role in slope stability on Vancouver Island. This thesis will attempt to clarify the relative role of trees and their roots on landslide initiation and address the following questions.

1. How does root density and root quality change after timber harvesting?
2. What time period after logging has the lowest root density and quality?
3. Are the existing unlogged tree roots healthy or is there extensive decay due to the trees age?

4. How do the roots of newly planted forests (clearcuts ≤11 years old) differ between second growth forests (>15 years old) and old growth forests (>300 years old)?
5. Does root shape and rooting depth have an effect on root density?
6. Does landslide frequency correspond to the root density and root quality low point after logging?
7. Where are windthrow and clearcut associated landslides likely to occur?
8. How does the density and magnitude of the landslides differ between windthrow, clearcut, natural, and road related landslides?
9. Are there any physical or mechanical effects of windthrow that cause slope instability?
10. How do the geotechnical properties of an organic layer commonly found near the failure slope of coastal British Columbia landslides affect slope stability?

## 1.4 Thesis Organization

Chapter 1 outlines the thesis project. This chapter also presents a literature review of the relevant research on windthrow, root reinforcement and organic layers conducted within forested terrain. Chapter 2, 3, and 4 are in journal paper format and intended to be read as standalone individual papers. Chapter 5 summarizes the conclusions for each chapter and discusses future research.

Chapter 2 describes the impact of windthrow on landslide initiation during the November 15, 2006 storm event. Spatial patterns between land uses in terrain, clearcut edge distance, and distance to the coastline are used to describe differences in the landslide density for each land use. Terrain attributes were statistically analysed to show the type of slope characteristics where windthrow landslides occur.

Chapter 3 presents the results for root decay and root reinforcement after logging. The root and terrain data from twenty-three cutblock and five windthrow associated landslides was used in the analysis. The research in this chapter will attempt to analyse whether logging affects root density and what other factors, if any, contribute to root decay. In addition, a landslide density will be determined for different harvest age groups.

Chapter 4 shows the results of soil testing on a basal organic rich layer located near the failure slope of two thirds of the 48 landslides visited in the field. The physical characteristics and geotechnical properties are analysed to identify attributes that adversely affect slope stability. Finally, Chapter 5 discusses and summarizes important conclusions for each chapter and makes recommendations for future work and possible forest practice changes.

## 1.5 Literature Review

### 1.5.1 Introduction

Literature on the following topics was reviewed for this thesis: 1) Windthrow, 2) Root Reinforcement and 3) Basal Organic Layer. The following is a summary of relevant research conducted for each subject area.

### 1.5.2 Windthrow

Windthrow is defined as the uprooting or breakage of trees due to wind (Mitchell et al., 2001). The uprooting of the tree roots causes the soil to be pushed up resulting in depressions (Marston, 2010). Windthrow can also result in extensive loss of forest canopy and exposure of mineral soil.

#### 1.5.2.1 Ecological Studies in the Pacific Northwest

A majority of windthrow studies have involved studying the effects of wind on trees from an ecological approach, with limited research on the effects on slope stability. In coastal British Columbia, research on windthrow has primarily involved the effects of clearcut logging on windthrow hazard and location (Mitchell et al., 2001; Rollerson et al., 2009). The topography, aspect, slope, age of cutblock and tree type can affect the windthrow hazard along cutblock edges (Mitchell et al., 2001). Predictably, the study by (Mitchell et al., 2001) found that topographic exposure to wind was a primary variable regarding windthrow risk along clearcut boundaries. Residual trees along clearcut boundaries are most vulnerable to windthrow (Ruel et al., 2002). Prevailing winds on the west coast of Vancouver Island are mainly from the southeast during the winter storm season exposing the south and east facing clearcut boundaries to a potential increased windthrow hazard (Environment Canada, 2009 a). Stathers et al. (1994) showed how wind damage is dependent upon wind direction and orientation of the valley. Winds perpendicular to the ridges affect the ridge tops with less damage on the valley bottom whereas winds parallel to the valleys affect ridge tops and the valley bottom.

A variable retention windthrow study was conducted by Western Forest Products Inc. on Vancouver Island between 2001 and 2009 (Rollerson et al., 2009). The study involved the field truthing of wind damage along cutblock boundaries. The researchers concluded that wind damage increases with increased elevation and slope gradient. They found that amabilis fir and western hemlock were most vulnerable whereas Douglas-fir was least vulnerable to windthrow. Furthermore, windward cutblock edges are most vulnerable to wind damage with slope positions such as ridges and upper slopes experiencing more wind damage. Recommendations from the study stated that to increase wind firmness along clearcut edges large retention strips should be used rather than narrow strips. In addition, they recommended establishing wider riparian and gully reserves in high risk areas, such as steep gully headwalls, where debris flow initiation can occur.

Ecological studies in Clayoquot Sound and the central coastal BC investigated the frequency and extent of natural disturbances on the landscape (Pearson, 2001, 2010). The research used a combination of aerial photograph interpretation and GIS databases to determine the extent of windthrow throughout the landscape. The results of the studies showed that there was no stand replacing wind disturbance for the last 140 years in Clayoquot Sound and for the central coastal BC. Similar studies were also conducted in Alaska to analyse the effects of windthrow on forest ecology (Nowacki and Kramer, 1998).

Research conducted by Sinton et al. (2000) on windthrow in the State of Oregon studied the effects of logging on windthrow events over the past 70 years in the Bull Run Basin. The study found that forest harvesting modified the effects of climate, topography and forests on windthrow disturbance. Logging resulted in as much as 80% of the windthrow occurring along clearcut edges during some windthrow events.

#### 1.5.2.2 Location and Causes of Windthrow and Related Landslides

Several studies focus upon the impact of weather on windthrow and landslides. Miles et al. (2008) researched the November 15, 2006 storm that caused most of the windthrow, related to this thesis project, which occurred on southwest Vancouver Island. The study concluded that wind and wind driven rain were major factors in the initiation of the windthrow related landslides. These findings were supported by Rulli et al. (2007), who previously modelled the effect of wind and topography on landslide initiation.

With respect to landslides, isolated intense storm cells and orographic precipitation can cause condensed areas or clusters of landslides (Guthrie and Evans, 2004; Loukas and Quick, 1994). However, challenges exist in the detection of these isolated storm cells due to the location and low number of weather stations (Guthrie et al., 2010; Miles et al., 2008). Regardless, their research indicates a higher occurrence of landslides during these storm events.

#### 1.5.2.3 Other Landslide Studies and Windthrow Mapping

Johnson et al. (2000) and Johnson and Wilcock (2002) researched windthrow and its effect on landslide initiation in Alaska. Tang et al. (1997) studied the effects of windthrow in Washington State and Rulli et al. (2007) in Italy. These studies showed a correlation between windthrow and landslide initiation.

Caslys Consulting (2007) also performed an extensive mapping project using automated change detection for the BC Ministry of Environment after the November 15, 2006 storm. They determined that windthrow and clearcut landslide densities were not significantly different. Guthrie et al. (2010) used the results from this change detection mapping and concluded that windthrow landslides were no more prevalent than clearcut landslides.

The evaluation of stereoscopic high resolution satellite imagery to map forest landscapes and landslides was completed on Vancouver Island by Kliparchuk and Collins (2003, 2008) and Kliparchuk et al. (2008). The research showed that high spatial resolution satellite imagery can be used to map remote forests for environmental concerns, identification of landslides and other forestry related reasons (Kliparchuk and Collins, 2008).

### 1.5.3 Root Reinforcement

Research on root reinforcement includes the study of how tree roots and soil combine to stabilize the forested hillslope. Contemporary research on Vancouver Island is somewhat limited on the subject of root reinforcement after logging resulting in a gap in knowledge.

#### 1.5.3.1 Previous Studies

It is well documented that landslide frequency increases after logging until the replanted trees replace the roots lost to decay from the original forest (Burroughs and Thomas, 1977; Ziemer, 1981a; Wu and Sidle, 1995; Sidle and Ochiai, 2006; Ammann et al., 2009). Sidle and Ochiai (2006) stated that the net reinforcement by roots is equal to the root decay by harvested or dead trees plus the root expansion and root decay of residual trees plus root expansion of the new trees. The sharp decrease in root strength between 3 and 8 years after logging is the location of maximum susceptibility to landslides (Figure 1.1).

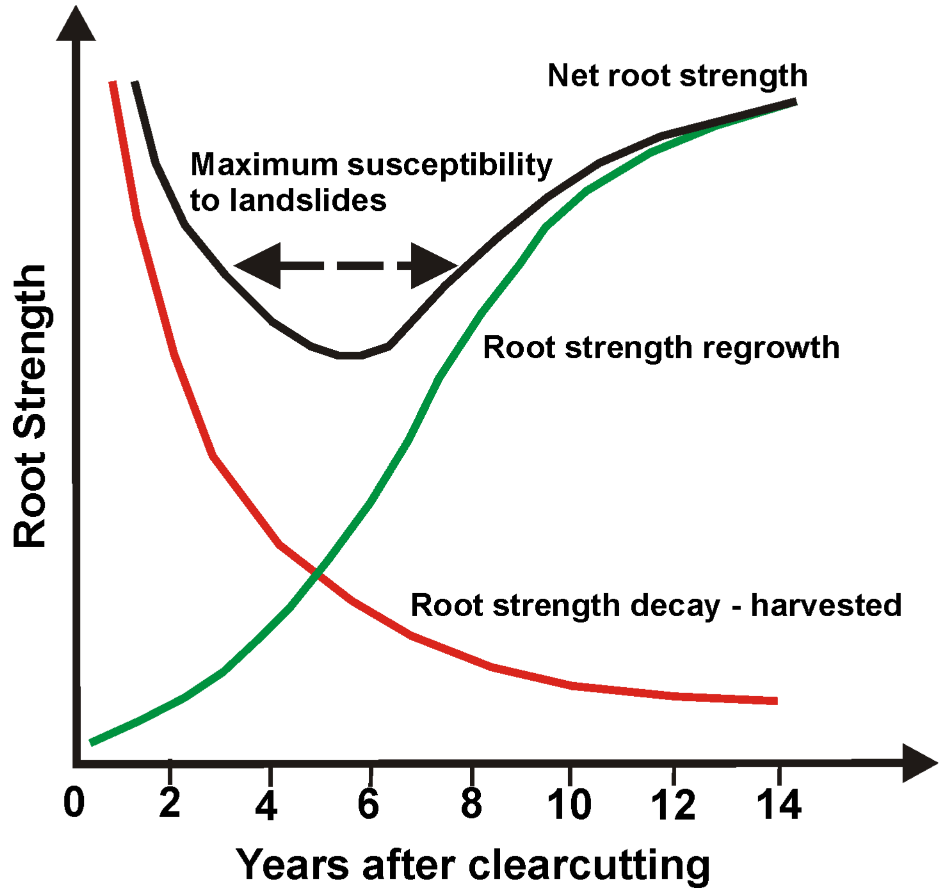



Figure 1.1: Idealized changes in root strength after timber harvesting, modified from Sidle and Ochiai, 2006.

Ziemer (1981a) found that 50% of the root reinforcement was lost within the first 2 years after harvest and that 90% was lost 9 years after harvest. In addition, it would take 15 years until the new plantation provides 50% of the original reinforcement and 26 years until it provides 100% reinforcement.

A recent Swiss study of tree death after a bark beetle outbreak found that within 15 to 20 years most of the root reinforcement was lost (Ammann et al., 2009). Regarding root reinforcement and landslides, a study on northern Vancouver Island by Horel (2006) showed that 27% of landslides occurred in the first year after logging and that 76% occurred within the first 5 years. Horel (2006) concluded that the high frequency of early landslides, particularly within the first year after harvest, may indicate factors other than root decay are causal in such instances. Although, according to Ziemer (1981a) there is 50% loss in root reinforcement within the first two years, possibly contributing to some of the landslides early after timber harvesting.

#### 1.5.3.2 Root Strength and Structure

Root strength and cohesion is dependent upon many factors such as tree species, root diameter, soil shear strength, soil moisture and logging history. Root strength testing done on different species shows a wide range of values. For western hemlock and Douglas-fir on the west coast of North America cohesion values vary between 5 and 94 kPa (Sidle and Ochiai, 2006). The strength and decay of roots also vary by geographic location and climate with more rapid decay in California than Alaska. Thin roots intersecting the landslide shear zone can also decrease the potential for slope failure (Stokes et al., 2009).

Root area ratio (RAR) is the ratio of root area with respect to soil area. Schmidt et al. (2001) found that natural forests on the Oregon Coast that were more than two centuries old had a high RAR. Conversely, recent clearcuts and second growth forests had a relatively low RAR. Root density research was also conducted using RAR by Abdi et al. (2009) in Iran and Bischetti et al. (2005) in Italy.

Research on the effect of root diameter has shown that smaller roots, less than 1 cm in diameter, have the largest impact on slope stability (Abe and Ziemer, 1991a). A decline in the number of small roots from decay is closely related to an increase in the number of landslides in the first few years after logging. Zhou et al. (1998) show that root diameters less than 5 mm have the largest effect on tensile strength. Within 7 years after harvesting, two thirds of the roots less than 2 mm in diameter will have decayed.

The effects of previous disturbances, such as; recent clearcut and selective logging, wildfires, and natural forests, have been examined on the Oregon Coast by Schmidt et al. (2001). Their results show that the mean lateral root cohesion in old growth forests, industrial forests, and recent clearcuts were 25.6 to 94.3 kPa, 6.8 to 23.2 kPa, and 1.5 to 6.7 kPa, respectively. The results show that the root cohesion in some industrial forests, that have been previously logged, burned, or commercially thinned up to 123 years old, are more like recent clearcuts than natural forests. These results show that the long-term impacts of previous disturbances can have a major effect on root reinforcement. The effects of herbicide use in clearcuts showed the lowest values for root strength of any sites in the study. A reduction in root strength in industrial forests may be due to an increase in hardwood and understory brush. Hardwoods are known to have higher tensile strength than conifers (O'Loughlin and Ziemer, 1982) but their root systems are generally less extensive.

A recent study by Pollen (2007) considers the relative proportions of root pull out and root breakage is a combination of soil moisture and shear strength. The study showed that smaller root diameters exceed pullout forces, whereas larger root pullout forces exceed breaking forces. The limiting root diameter between root pullout and root breakage was a factor of varying soil shear strength.

Roering et al. (2003) studied the effect of tree spacing, vigour, and size on root reinforcement on the Oregon Coast. The existence of gaps in the forest had an adverse effect on slope stability. Hardwood species and diseased conifers were also present in areas where landslides occurred. Although the natural spacing of hardwoods was less than conifers, the smaller rooting systems of the hardwood have a reduced effect on root reinforcement. Research by Watson et al. (1999) in New Zealand on Radiata Pine has shown an increase in landslide frequency due to increased spacing when planting seedlings. The researchers found that a trend of planting to lower densities may be contributing to decreased slope stability. The effects of increased root reinforcement have also been shown by Ziemer (1981a) when a site is selectively logged. Selective logging allows residual tree roots to expand into the root space left by the decaying roots of the original trees.

#### 1.5.3.3 Forest Health

Poor forest health, in particular root disease, has been shown to lead to low root density in some old growth stands (Nowacki and Kramer, 1998; Dowling, 2003). The health of the trees within the old growth forests are another contributing factor for poor quality roots in windthrow. Many old growth trees have been subject to centuries of damage due to wind (Pearson, 2001), disease (Nowacki and Kramer, 1998) and fire resulting in unhealthy forests. Previous windthrow modelling research has focussed on how wind affects tree health and root systems along clearcut edges (Mitchell et al., 2001; Yang et al., 2006).

### 1.5.4 Basal Organic Layer

A basal organic rich layer is frequently identified along the failure slope of landslides in coastal British Columbia. Research on this organic layer is limited. A majority of studies on organic soil/layers were undertaken over the past 40 years. These studies were primarily soil science based with a focus on forest soils.

#### 1.5.4.1 Previous Studies

Martin and Lowe (1989) and Sanborn and Lavkulich (1989 a, b) researched the soil properties of an organic rich root mat and root channels on southwest Vancouver Island and Coquitlam, BC. The organic rich layers were present primarily in the B horizon of Ferro-Humic Podzols (Carter et al., 1985). This research showed that the accumulations of organic matter were primarily derived from humified roots and had high organic carbon content >30%.

An overview of landslides in organic soils was recently completed by the Ministry of Forest and Range (Campbell et al., 2010). They determined that the presence of organic soil overlying low permeability soils or rock increased the risk of landslides. In addition, where organic rich soil layers were identified on gentle slopes, landslide hazard increased relative to slopes absent of organic rich layers. Furthermore, timber harvesting, road construction and windthrow are known to contribute to landslide hazard where organic rich layers are present.

A 1970's study by Lewis and Lavkulich (1972) included an examination of the relationship between elevation and organic soil (Folisol) accumulation. Folisols are organic soils that develop at the surface and not at depth as with the organic layer researched for this current project. Folisols are an organic soil and develop along poorly drained bedrock surfaces at the failure slope of some landslides (NRC, 1998). They found that the humic layer or horizon thickness increased with elevation.

A thesis project completed by Nagle (2000) near Prince Rupert, BC also examined the terrain attributes and geotechnical soil properties of Folisols on slope stability. The study determined that slope angle, soil cohesion, groundwater and tree roots affected the stability of the Folisol.

#### 1.5.4.2 Macropores and Groundwater Flow

Macropores are described as soil voids, both lateral and vertical, that are conduits for groundwater flow (Beven and Germann, 1982). Macropores develop in several ways including: the deterioration of roots, animal burrows, and cracks within the soil matrix (Aubertin, 1971). The macropores channel and route water through the subsurface, hence reducing pore water soil pressure and slope instability (Ziemer, 1992). Conversely, the collapse and blockage of macropores can cause an increase in slope instability (Campbell et al. 2010).

Bedrock fractures also act as pathways for groundwater flow, thus reducing pore water pressures in the overlying soils (Fannin et al., 2000). Related blockages in bedrock fractures from organic and mineral soil accumulations can also reduce groundwater flow and decrease slope stability (Johnson and Sitar, 1990).

#### 1.5.4.3 Geotechnical Characteristics

Peat soils are classified as to their degree of humification according to the van Post classification. The von Post classification uses a scale of 1 to10 to determine the degree of humification (Table 1.1). Although, the organic layer in this study is not a peat soil, some methods of classification for peat soil are applicable.

The higher the degree of humification or decomposition results in a lower permeability of the organic soil (Hobbs, 1986). Lower permeability results in higher pore water pressures leading to a higher landslide risk at organic soil/layer locations.

Table 1.1: Degree of humification, von Post Classification, modified from Landva and Pheeney, 1980.

| Degree of humification | Decomposition | Plant structure | Content of amorphous material | Material extruded | Nature of residue |
|---|---|---|---|---|---|
| $H_1$ | None | Easily identified | None | Clear, colourless water | |
| $H_2$ | Insignificant | Easily identified | None | Yellowish water | |
| $H_3$ | Very slight | Still identifiable | Slight | Brown, muddy water; no peat | Not pasty |
| $H_4$ | Slight | Not easily identified | Some | Dark brown, muddy water; no peat | Somewhat pasty |
| $H_5$ | Moderate | Recognizable, but vague | Considerable | Muddy water and some peat | Strongly pasty |
| $H_6$ | Moderately strong | Indistinct (more distinct after squeezing) | Considerable | About one third of peat squeezed out; water dark brown | |
| $H_7$ | Strong | Faintly recognizable | High | About one half of peat squeezed out; any water very dark brown | $H_6$ to $H_8$ Fibres and roots more resistant to decomposition |
| $H_8$ | Very strong | Very indistinct | High | About two thirds of peat squeezed out; also some pasty water | |
| $H_9$ | Nearly complete | Almost unrecognizable | | Nearly all the peat squeezed out as a fairly uniform paste | |
| $H_{10}$ | Complete | Not discernible | | All the peat passes between the fingers; no free water visible | |

### 1.5.5 Summary

The interdependence of these factors: roots, windthrow and organic rich layers all play a role in slope stability. This literature review is a comprehensive introduction to the terms and ideas that will be discussed in the following chapters of this thesis.

# 2: Windthrow and Its Effects on Landslide Initiation, Southwestern Vancouver Island, British Columbia

## 2.1 Introduction

The west coast of Vancouver Island is prone to frequent winter storms with high winds causing landslides and windthrow. The term windthrow or blowdown refers to the uprooting or breaking of trees due to wind (Mitchell et al., 2001). Wind firmness is the ability of a tree to resist wind pressures resulting in wind damage. The ability of the tree to resist wind damage can depend on the cutblock boundary location and the alignment of the boundary to the dominant wind direction (Stathers et al., 1994; Rowan et al., 2003). Trees can also develop wind firmness after being exposed to wind forces for several years after logging or by their location in the upper levels of the forest canopy. There has been limited research on the influence of windthrow on slope stability in British Columbia. A large storm event between November 12 and 17, 2006, hereafter referred to as the "*November 15, 2006 storm"*, which resulted in large areas of windthrow and numerous landslides has allowed an excellent opportunity to research the effects of windthrow on landslide initiation over a limited areal extent of southern Vancouver Island. Based on Western Forest Products Inc. (WFP) landslide event reports approximately 20% of the landslide events were caused by up to three other storm events during the winter of 2006/2007. There have been studies on the probability of windthrow events and how it is affected by topography and cutblock location (Mitchell et al., 2001) but no actual analysis of landslide generation. A variable retention windthrow monitoring project was also conducted by Western Forest Products (WFP) on Vancouver Island focussing on areas most prone to windthrow due to logging (Rollerson et al., 2009). Research on windthrow and its effect on landslide initiation was conducted in Alaska (Johnson et al., 2000; Johnson and Wilcock, 2002) in Washington State (Tang et al., 1997) and in Italy (Rulli et al., 2007). These studies found an association between windthrow and landslides as part of a larger landslide study.

Southwestern Vancouver Island experienced several large storm events between November 2006 and March 2007, which triggered over 230 landslides (Figure 2.1). The storm event on November 15, 2006 caused a majority of the landslides in the Klanawa, Sarita, and Nitinat River valleys, and was accompanied by high wind gusts in excess of 100 km/hour and 24-hour rainfall exceeding 200 mm. This research involved a field investigation of forty-eight open slope cutblock and windthrow-associated landslides and mapping 233 landslides with satellite imagery and Geographic Information System (GIS) analysis. Previous slope stability research has found that the loss of root reinforcement and forest canopy, exposed soil and diverted surface water flows provide a strong causal basis for windthrow generated landslides. The objective of this chapter is to identify terrain, land uses, and weather conditions where windthrow landslides are likely to occur.

The goals of this chapter are to:

1) determine the attributes that contribute to windthrow landslide initiation;
2) compare the field data analysis to the GIS analysis;
3) analyse the spatial distribution of landslides and windthrow; and
4) compare the landslide density for windthrow landslides to other land uses and other landslide studies.

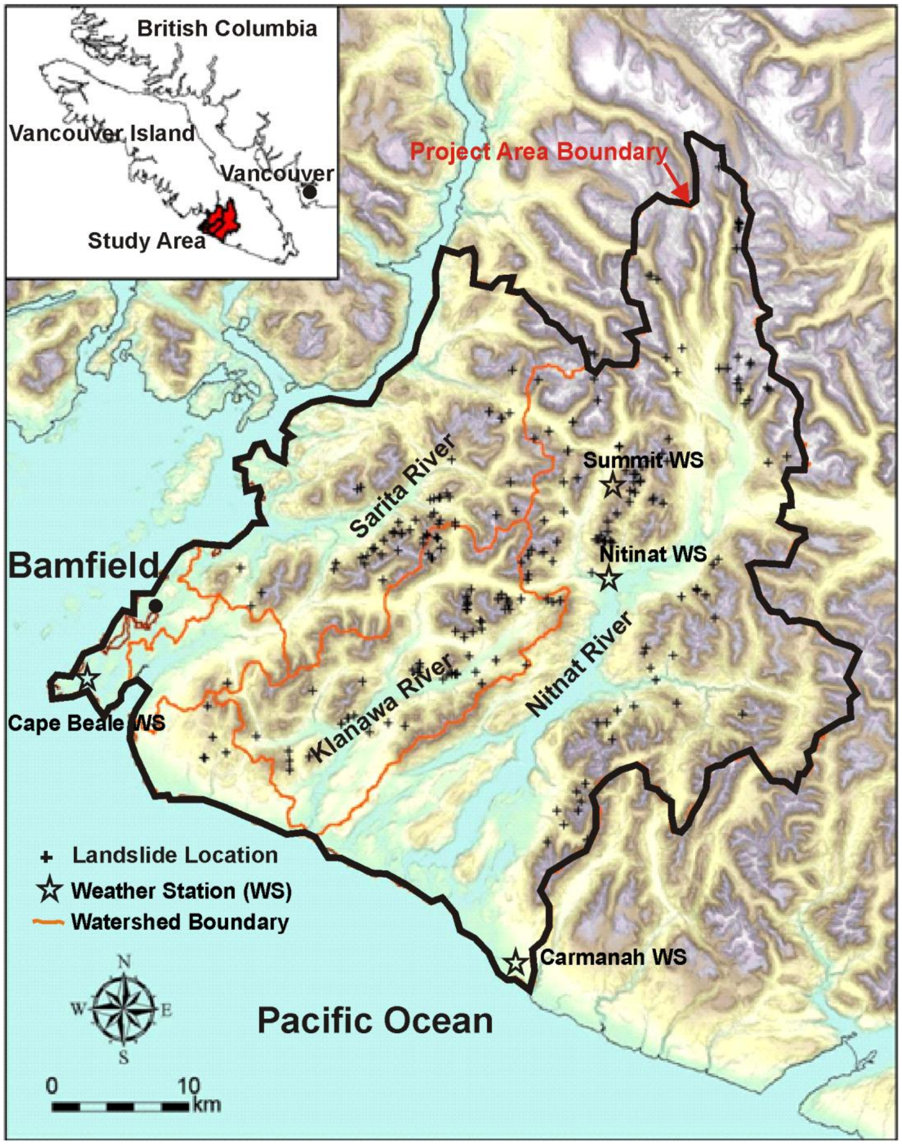



Figure 2.1: Project area location map.

## 2.2 Setting

The research area is located on southwestern Vancouver Island near the community of Bamfield, approximately 160 km west of Vancouver, BC. The project area includes the Nitinat, Klanawa and Sarita River watersheds and is bounded to the west by Pacific Rim National Park and the Pacific Ocean, to the south and east by the Cowichan

Lake watershed and Carmanah Provincial Park, and to the north by Alberni Inlet. A majority of the area lies within Western Forest Products (WFP) and Teal Cedar Products Tree Farm Licences (TFL), which include TFL 44 and 46, respectively, as well as other crown land licences such as Forest Licences and BC Timber Sales. Small parcels of private land also exist, primarily at low elevations, in the Sarita and Nitinat River valleys.

The Vancouver Island Ranges are the dominant mountain range on Vancouver Island and trend northwest southeast through the study area. Pleistocene glaciations have carved U shaped valleys and fiords throughout the area and deposited thick till and glaciofluvial sediments on lower to middle slopes (Holland, 1964). Colluvium dominates the upper valley slopes and fluvial deposits exist on the valley bottoms.

Most of the bedrock geology is Jurassic, consisting of granitic intrusive rocks from the Island Plutonic Suite, West Coast Crystalline Complex, and volcanic rocks from the Bonanza Group (Massey et al., 2005). Lesser amounts of Upper Eocene and Triassic sedimentary rocks from the Vancouver and Carmanah Groups also exist in the area.

The climate is wet and humid with cool summers, mild winters, and low amounts of snowfall (Green and Klinka, 1994). Major rainfall events from moist Pacific air masses occur between October and March, and are associated with significant landslide activity (Jakob, 2000). The study area contains two variants of the Coastal Western Hemlock (CWH) Biogeoclimatic Zone: 1) the submontane very wet maritime variant (CWHvm1) between sea level and 600 m elevation and 2) the montane very wet maritime variant (CWHvm2) between elevations of 600 m and 1000 m (Green and Klinka, 1994). The CWH forests are dominated by tree species such as western hemlock (*Tsuga heterophylla)*, amabilis fir or balsam (*Abies amabilis)*, western redcedar (*Thuja plicata)*, and lesser amounts of Douglas-fir (*Pseudotsuga menziesii),* and Sitka spruce (*Picea sitchensis).*

The mean annual precipitation for the Nitinat River Hatchery weather station is 4000 mm with just over 2800 mm of precipitation between October and March (Figure 2.2). There was over 3900 mm of precipitation between October 2006 and March 2007, 40% greater than the mean precipitation for the same period.

The November 15 2006 storm was associated with most of the landslides and had a total rainfall of 380 mm with a daily maximum of 220 mm at the Summit Forest Service weather station (Figure 2.3). The storm had a 15-year and 7-year return period based on 12-hour and 24-hour precipitation data, respectively (Miles et al., 2008). In addition, the rain gauges likely under estimated the amount of rain due to a snow-cap covering the rain gauges and wind driving the rain at an oblique angle to the rain buckets (Miles et al., 2008; Rulli et al., 2007). Since the freezing level was as low as 600 m before November 15 and then rose to over 2000 m during the storm, the snowpack probably melted rapidly compounding the effects of the rainstorm (Miles et al., 2008). Warm temperatures with high wind speeds combined with intense precipitation, likely caused condensation melting of the pre-existing snow pack (Miles et al., 2008; Floyd and Weiler, 2008). However, it is difficult to estimate the increase in effective precipitation from this rain on snow event. Wet antecedent conditions, with nearly 450 mm of rain in the first week of November, may have limited the amount of precipitation the soil was able to absorb during the storm.

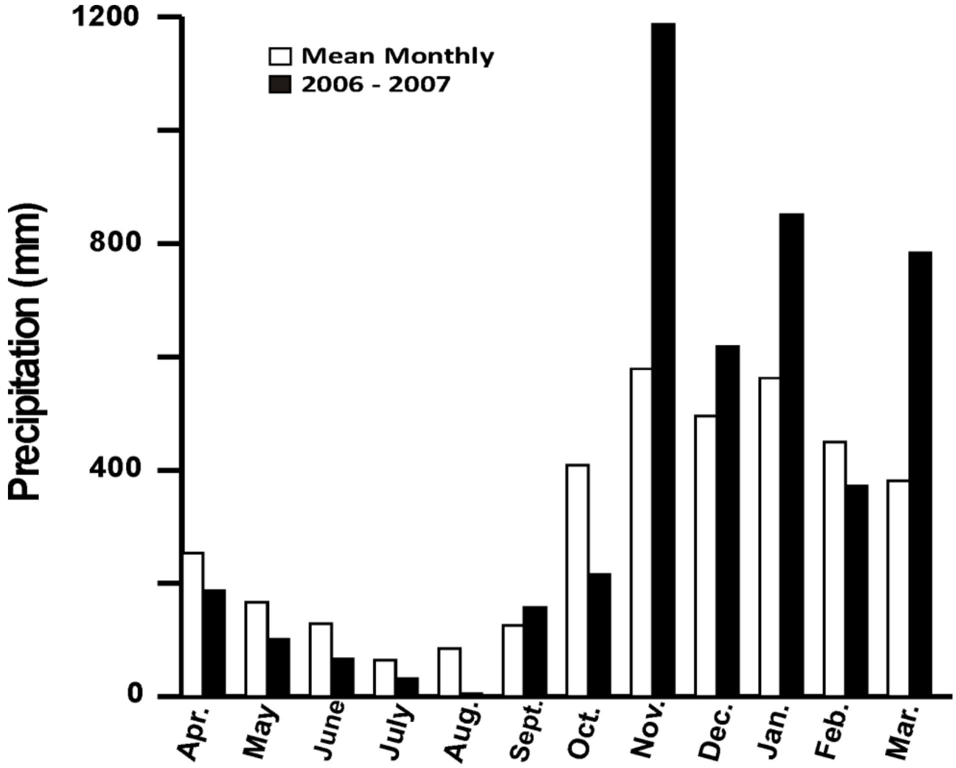



Figure 2.2: Nitinat River Hatchery weather station precipitation (Mean Monthly and 2006/2007) Environment Canada climate normals and averages 1971-2000 (Environment Canada, 2009b).

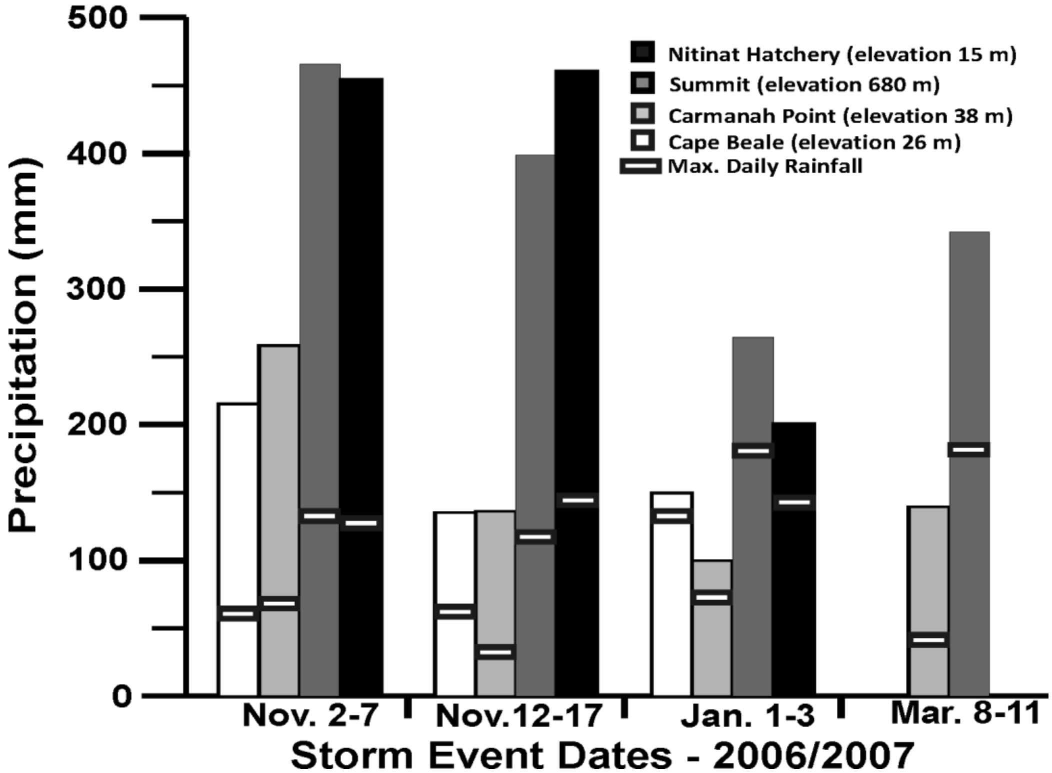



Figure 2.3: Precipitation for four main storm events at Environment Canada weather stations Cape Beale, Carmanah Point, and Nitinat River Hatchery and MOFR Summit weather station (Environment Canada, 2009a; MOFR, 2009). The coastal weather stations received considerably less precipitation than the inland stations.

Previous studies (cf Church and Miles, 1987; Caine, 1980) have shown that high amounts of precipitation occurring over a short time frame combined with high wind speeds can contribute to an increase in landslide initiation (Forest Practices Board, 2009) (Figure 2.4). Windthrow risk is higher with wet soil conditions or a high water table (Everham and Brokaw, 1996). Heavy rain and wind coincided, resulting in the rain impacting slopes at high velocities, increasing the rate of water infiltration into the soil.

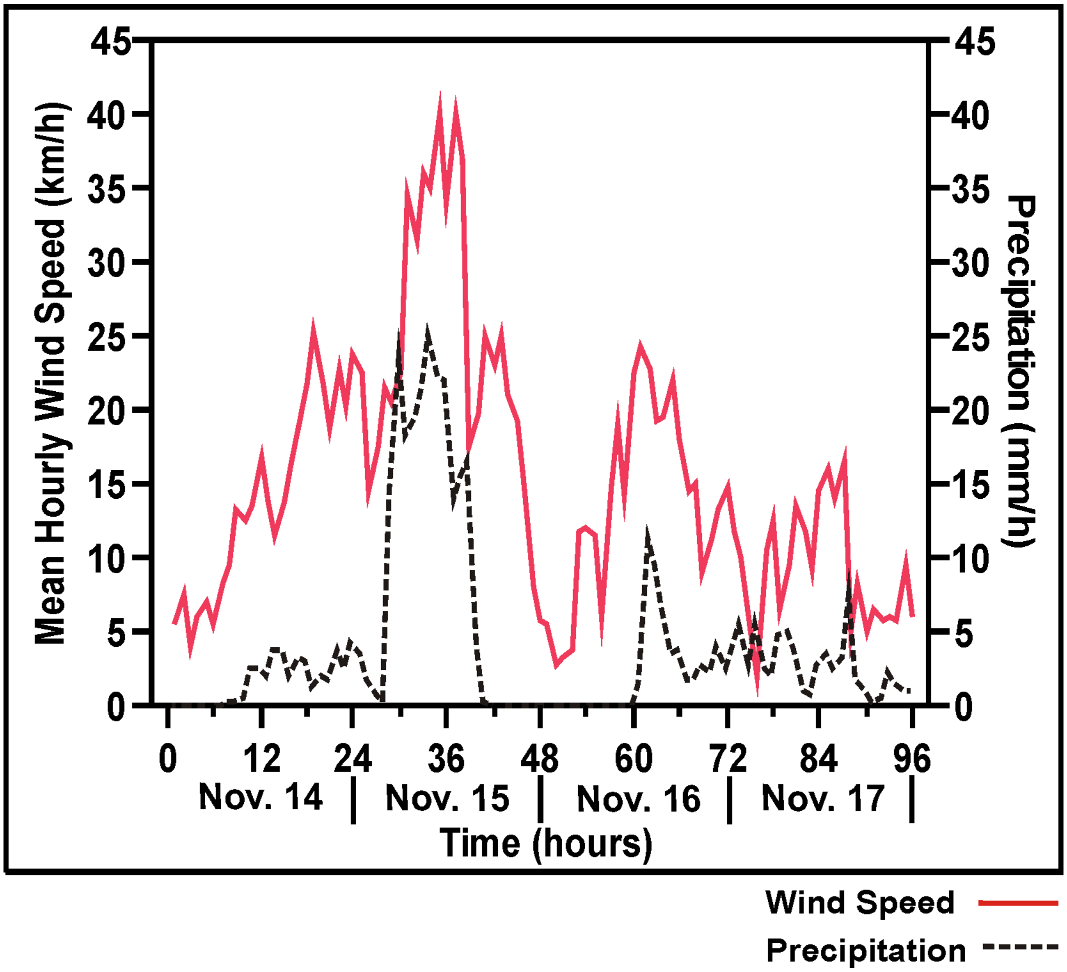



Figure 2.4: Timing of wind and precipitation during November storm event at MOFR Summit weather station (MOFR, 2009). Wind speeds are average hourly and unrecorded gusts were greater than 100 km/h as illustrated in WFP landslide reports.

## 2.3 Methods

### 2.3.1 Sample Design and Data Collection

Two data sets were utilized for this study. First, a field study with detailed soil and terrain data on forty-eight open slope landslides was initiated between May and July, 2007. A second database was developed in the office by identifying 233 landslides on SPOT 2007 satellite imagery and digital colour orthophotographs (orthophotos) and analysing with GIS (Table 2.1). The field study was conducted differently than most landslide studies. It is common practice to review aerial photographs and satellite imagery prior to conducting field truthing. The storms responsible for a majority of the windthrow and landslides occurred in the winter of 2006/2007. Consequently, field data was collected before updated satellite imagery and aerial photographs were available. To allow the sampling of fresh landslides triggered by similar precipitation and climatic values, only slope failures that occurred between November 2006 and March 2007 were included. Selection of landslides over a limited areal extent in the Sarita, Klanawa, and Nitinat watersheds reduced the variability from climate, geology and vegetation.

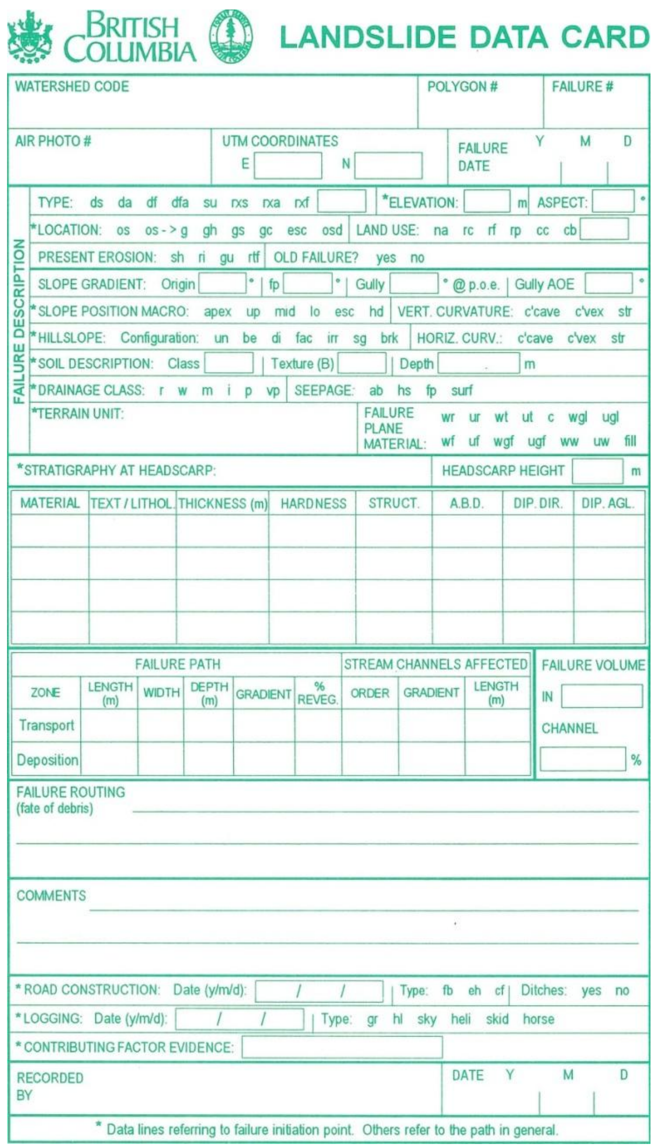
Table 2.1: Types of remote sensing imagery utilized for the research project. SPOT 2004 and 2006 imagery was used by Caslys for change detection with a resolution of 2.5 m and 5 m, respectively.

| Imagery Type | **Resolution** | **Scale** | **Source** | **Date** |
|---|---|---|---|---|
| Colour Digital Orthophotographs | 0.3 m | 1:30,000 | WFP | May/June 2007 |
| SPOT Satellite Imagery | 2.5 m | N/A | MOE | 2007 |

Terrain and soil data were collected in the field for 16 clearcuts, 8 second growth and 24 windthrow-associated landslides. Second growth stands were replanted clearcuts greater than 15 years old. The immediate area above all landslides was examined to ensure there was no road drainage influence above the landslide initiation zone.

The criteria for identifying landslides in the field included size and morphology, including intiation and runnout zones. Because the slides all happened the previous fall, no minimum size was set, with the smallest slides being slightly below 400 $m^2$ and the largest at 39,000 $m^2$. Landslides were considered to have a single initiation point; if two initiation tracks merged in the runout zone, this was considered two landslides. Diverging runout zones were classified as one landslide.  Landslides were categorized as debris avalanches, debris flows and debris slides and their association to clearcut and windthrow was noted. Rockslides were excluded from the landslide inventory.

Terrain attributes such as slope gradient, soil depth and type, slope curvature and position, aspect, drainage, landslide dimensions, and elevation were recorded on a BC Forest Service Landslide Data Card (Figure 2.5). The landslides were located using landslide event reports and reconnaissance maps from WFP.



BRITISH COLUMBIA LANDSLIDE DATA CARD

WATERSHED CODE | POLYGON # | FAILURE #

AIR PHOTO # | UTM COORDINATES E N | FAILURE DATE Y M D

FAILURE DESCRIPTION

TYPE: ds da df dfa su rxs rxa rxf | *ELEVATION: m | ASPECT: °

*LOCATION: os os->g gh gs gc esc osd | LAND USE: na rc rf rp cc cb

PRESENT EROSION: sh ri gu rtf | OLD FAILURE? yes no

SLOPE GRADIENT: Origin ° | fp ° | Gully ° @ p.o.e. | Gully AOE °

*SLOPE POSITION MACRO: apex up mid lo esc hd | VERT. CURVATURE: c'cave c'vex str

*HILLSLOPE: Configuration: un be di fac irr sg brk | HORIZ. CURV.: c'cave c'vex str

*SOIL DESCRIPTION: Class | Texture (B) | Depth m

*DRAINAGE CLASS: r w m i p vp | SEEPAGE: ab hs fp surf

*TERRAIN UNIT: | FAILURE PLANE MATERIAL: wr ur wt ut c wgl ugl wf uf wgf ugf ww uw fill

*STRATIGRAPHY AT HEADSCARP: | HEADSCARP HEIGHT m

| MATERIAL | TEXT / LITHOL. | THICKNESS (m) | HARDNESS | STRUCT. | A.B.D. | DIP. DIR. | DIP. AGL. |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

| | FAILURE PATH | | | | | STREAM CHANNELS AFFECTED | | |
|---|---|---|---|---|---|---|---|---|
| ZONE | LENGTH (m) | WIDTH | DEPTH (m) | GRADIENT | % REVEG. | ORDER | GRADIENT | LENGTH (m) |
| Transport | | | | | | | | |
| Deposition | | | | | | | | |

FAILURE VOLUME IN CHANNEL %

FAILURE ROUTING (fate of debris)

COMMENTS

* ROAD CONSTRUCTION: Date (y/m/d): / / | Type: fb eh cf | Ditches: yes no

* LOGGING: Date (y/m/d): / / | Type: gr hl sky heli skid horse

* CONTRIBUTING FACTOR EVIDENCE:

RECORDED BY | DATE Y M D

* Data lines referring to failure initiation point. Others refer to the path in general.

Figure 2.5: BC Forest Service Landslide Data Card used for data collection (MOFR, 1996).

The GIS landslide database was identified from SPOT 2007 satellite imagery and categorized by land use (clearcut, road, windthrow and natural) and divided into geomorphic location (open slope or gullied terrain) (Table 2.2). Road related landslides included both cutslope and fillslope (road prism) failures as well as road drainage influenced landslides immediately below the road prism. Windthrow landslides were failures occurring within a windthrow patch (Figure 2.6, Figure 2.7, Figure 2.8). Within the project area, natural landslides are those that occurred in undisturbed terrain, exclusive of logging activity (clearcuts and roads) or windthrow. A Digital Elevation Model (DEM) was developed using 25 m Terrain Resource Information Management (TRIM) data. Data such as slope gradient, elevation, aspect, landslide area and dimensions, geomorphic location, landslide type, harvest age, forest type, bedrock type, distance from coast, and distance from a clearcut edge was determined from SPOT 2007 satellite imagery and the DEM using selected ArcGIS tools and extensions.

Table 2.2: Categories for variables used in study.

| **Land Use Categories** | **Combined Land Use Category by Geomorphic Location** |
|---|---|
| C - Clearcut<br>W - Windthrow<br>N - Natural<br>R - Road<br>OG - Old Growth<br>SG - Second Growth<br>RS - Reserve | OSC - Open Slope Clearcut<br>GC - Gully Clearcut<br>OSW - Open Slope Windthrow<br>GW - Gully Windthrow<br>GN - Gully Natural |
| **Geomorphic Location**<br>OS - Open Slope<br>G - Gully | **Statistical Abbreviations**<br>n – number of landslides or objects<br>ns – not significant |

Landslides, windthrow patches, new roads and new clearcuts were identified by Caslys Consulting for the British Columbia Ministry of Environment (MOE) using automated change detection between sequential 2004, 2006 and 2007 SPOT satellite images and were saved on GIS shape files (Caslys Consulting, 2007).

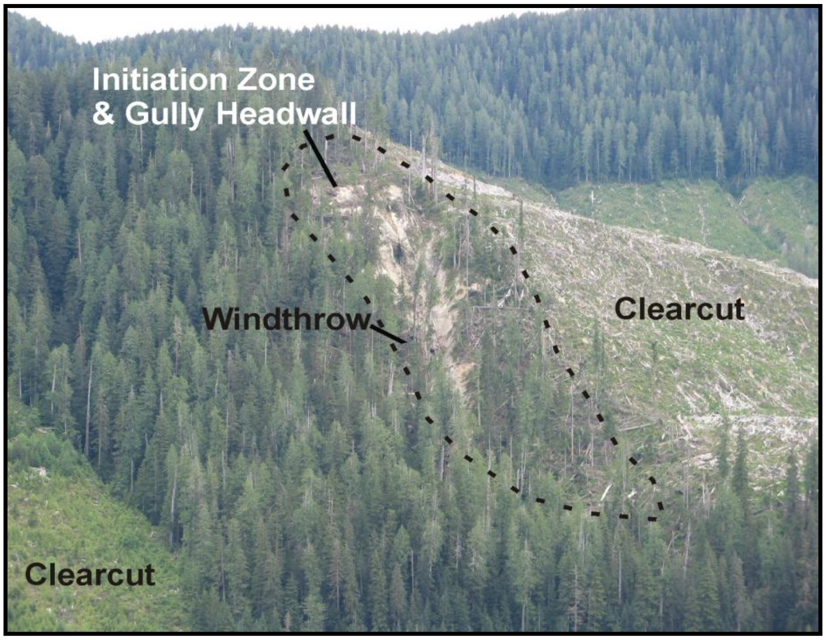



Figure 2.6: A windthrow related landslide (debris flow) located within a gully and adjacent to recent clearcut.

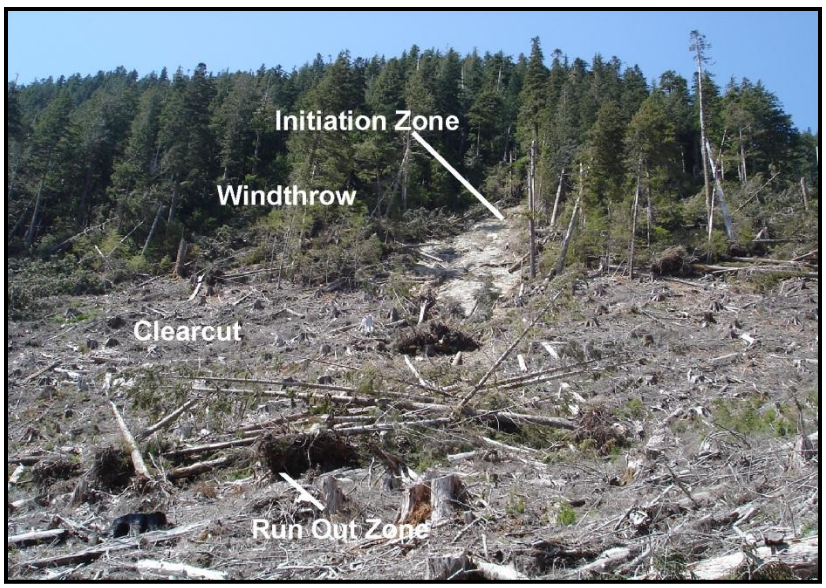



Figure 2.7: Debris slide initiated in windthrow and runout zone into recent clearcut.

The automated change detection project completed by Caslys was unrelated to this research; however, this thesis utilized some of their GIS shape files identifying landslides, windthrow and clearcuts. Automated change detection is a process of combining two SPOT satellite images from different years (eg. 2004 – 2006 and 2006 - 2007) into a single stacked image (Guthrie et al., 2010). The 2004 and 2007 SPOT imagery were 2.5 m resolution whereas the 2006 SPOT imagery was 5 m resolution. Consequently, when the 2004 and 2007 imagery was stacked over the lower resolution 2006 imagery the resolution of the stacked image for automated change detection was reduced to 5 m. Areas with no change detected appear blue with the filter and areas with change appeared red such as new roads, clearcuts, landslides and windthrow (Guthrie et al., 2010). The author of this thesis completed a landslide and windthrow inventory by editing the existing MOE shape files, using WFP landslide reports, reconnaissance maps, colour digital orthophotos and field reconnaissance photographs. Orthophoto imagery (Figure 2.21) in conjunction with reconnaissance maps was used to identify additional windthrow or landslides not detected using the automated change detection method. The WFP orthophoto imagery was a mosaic of several hundred aerial photographs that were digitally joined. SPOT 2007 satellite imagery was also used to identify clearcuts newer than 10 years on a digital forest cover map updated to 1997. The MOE 2007 SPOT satellite imagery was 2.5 m resolution and the WFP orthophoto imagery was 0.3 m resolution (Table 2.1). Previous research by Kliparchuk and Collins (2003, 2008) and Collins and Kliparchuk (2004) have shown the effectiveness of high resolution satellite imagery in mapping changes in forest structure and condition as well as geomorphic changes.

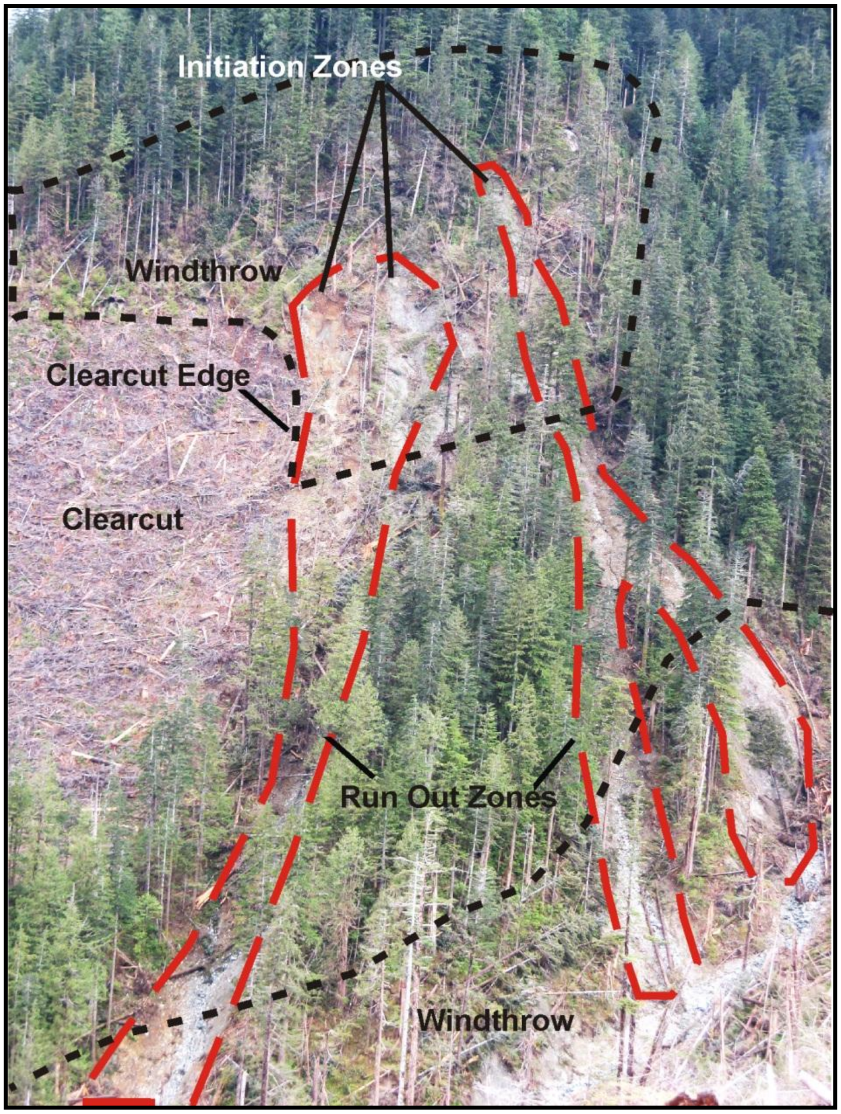



Figure 2.8: Multiple windthrow related landslides clustering adjacent to <1 year old clearcut. Landslide on left side is 5 m outside of clearcut boundary.

### 2.3.2 Data Analysis

A WFP harvest year overview map and digital forest cover map was used to identify the harvest age for each clearcut and forest polygon where landslides were present. All field and GIS terrain attributes were compiled into a spreadsheet and then statistically analysed.

A univariate statistical analysis was conducted using Kruskall-Wallis tests and $X^2$ tests. The residuals were tested to ensure they were from the normal distribution. A significance level of $P \leq 0.05$ was considered significant and therefore evidence to reject the null hypothesis.

Contingency tests were conducted when there was nominal or ordinal data for both the independent and dependent variables. A two-tailed $X^2$/ Fisher's Exact test or a Pearson $X^2$ was used for the contingency tests. Due to the small field data set (n=48) a majority of these tests were suspect due to 20% of cells having counts less than five. These cases were identified with an asterisk in the summary tables. A significance level of $P \leq 0.10$ was considered significant and therefore evidence to reject the null hypothesis. Unlike the t-tests, the significance level for the contingency tests was $P \leq 0.10$, as the data required more flexibility due to the small sample size used (Wolter et al., 2010).

## 2.4 Results

### 2.4.1 Landslide Description

#### 2.4.1.1 GIS Data Analysis

A total of 233 landslides were classified according to type, land use, and geomorphic expression using 2.5 m resolution 2007 SPOT satellite imagery. Road failures accounted for 34% of the total number of landslides, while windthrow, clearcuts and natural landslides accounted for 33%, 25% and 8%, respectively. Debris flows were the dominant landslide type accounting for 89% of all slope failures. They accounted for 92% of road failures, 100% of clearcut failures, 74% of windthrow failures, and 100% of natural failures. In terms of geomorphic position, debris slides (Varnes, 1978) made up a majority (62%) of open slope windthrow landslides. The mean slope length for debris flows and debris slides in all land uses was 556 m and 113 m, respectively. The longer length resulted in larger impacts for debris flows with a total of one-hundred fifty (72%) impacting streams whereas only five (19%) of debris slides impacted streams. The impact of debris flows on streams and lakes in the Sarita River valley is demonstrated in Figure 2.9. Within the total project area, 58% of the clearcut landslides impacted streams whereas, only 38% of windthrow landslides impacted streams.

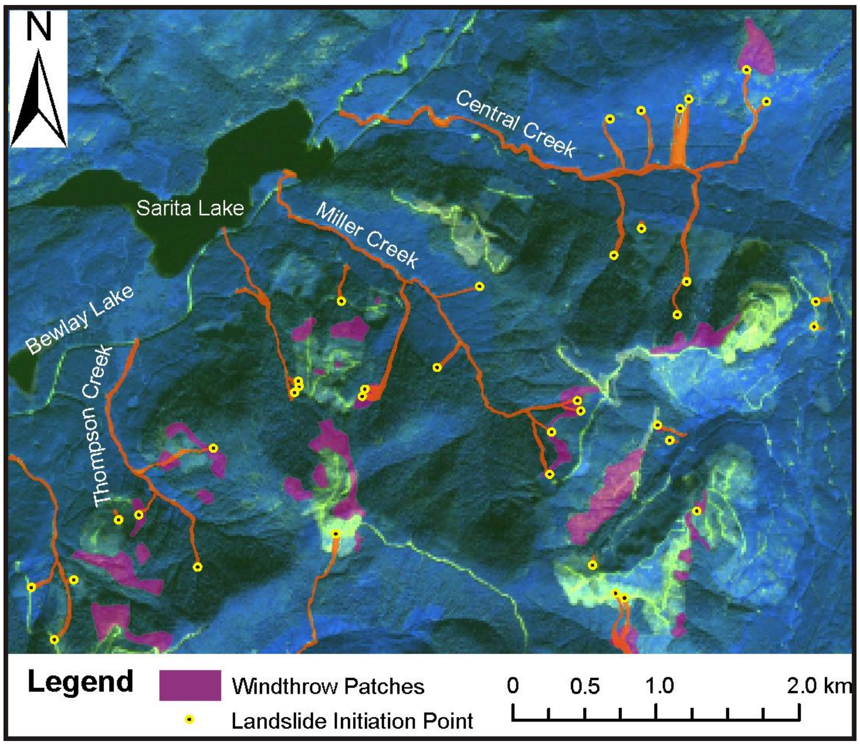



Figure 2.9: The debris flow routes are shown in orange impacting the Sarita River valley. Sarita Lake was impacted by 23 debris flows in Central, Miller and Thompson Creeks.

#### 2.4.1.2 Comparing GIS and Field Data

The differences between GIS and field data analysis were analyzed to determine the reliability of the GIS results. In total, 48 open slope landslides were measured in the field and the same 48 GIS landslides were used for comparison. The difference in slope, elevation, and aspect are compared (Table 2.3).

Table 2.3: Comparison of GIS and field data sets for 48 ground-truthed landslides. * C = clearcut **W = windthrow (n = 48)

| Terrain Attribute | GIS | | Field | |
|---|---|---|---|---|
| | *C | **W | *C | **W |
| Slope (°) | 32 | 33 | 34 | 39 |
| Elevation | 437 | 502 | 435 | 506 |
| Aspect (3 most common) | NNE to ESE | ENE to SSE | ENE to SSE | ENE to SSE |

The mean slope for GIS was lower than the field measurements for clearcut and windthrow associated landslides. The field slope measurements tend to be more reliable at showing differences between clearcut and windthrow landslides than GIS. However, the GIS and field data show no significant difference with respect to landslide elevation and aspect.

Landslide slope gradient was calculated from the initiation point on the DEM and grouped into 5° bins using GIS (Figure 2.10). The overall landslide distribution appears to be positively skewed toward the lower slopes. The majority of landslides occurred in the 25° to 40° range. A Kruskall-Wallis test showed an overall significant difference (p=0.01) in slope between land uses. However, compared to field measurements, the DEM underestimates the actual slope by approximately 2° and 5° for clearcut and windthrow landslides, respectively (Table 2.3). This could be due to a difference in forest canopy levels at the clearcut boundaries or errors in the DEM. Therefore, the GIS slopes are used only to illustrate the general distribution of slope gradients between land uses.

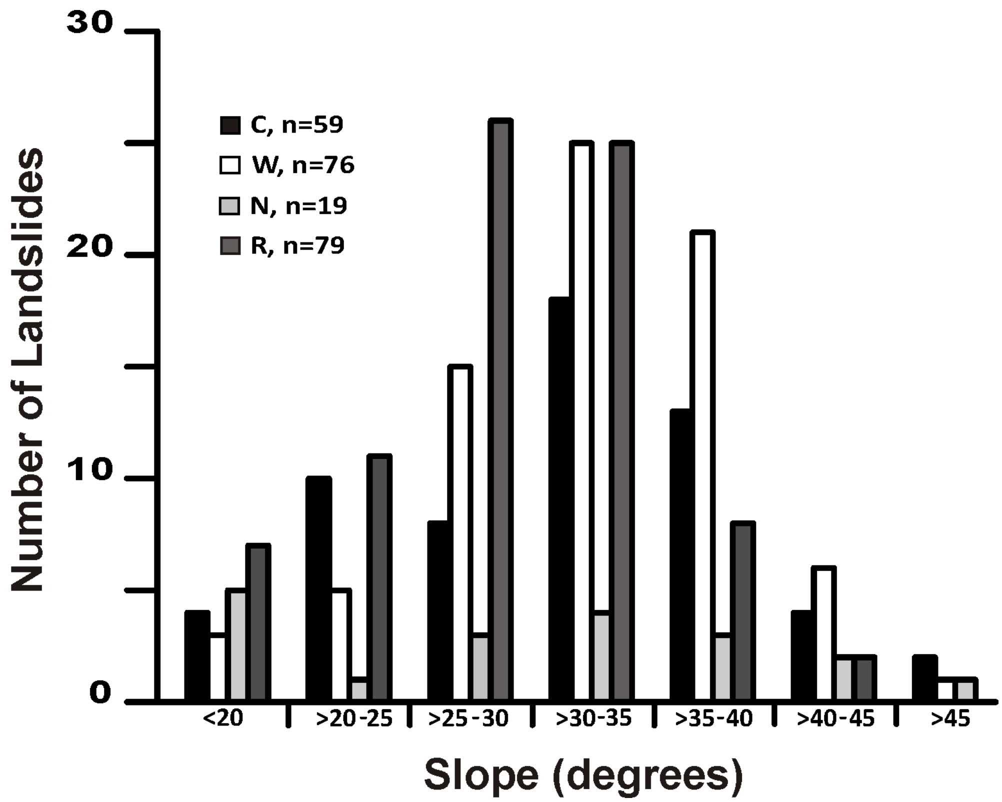



Figure 2.10: Initiation slope gradient comparison between four land uses for satellite identified landslides. C = clearcut, W = windthrow, N = natural and R = Road (n = 233)

Mean GIS slope values ranged between 28° and 33° (Table 2.4). There is no significant difference ($p>0.05$) in slope angle between road, clearcut, natural, and windthrow associated landslides. The influence of geomorphic location (open slope or gully) was analysed for clearcut, windthrow, and natural landslides. There was a 2° difference in mean slope gradient between open slope clearcut and windthrow landslides and a 1° difference between gullied clearcut and windthrow landslides but there was no significant difference ($p>0.05$) for slope gradient between land uses or geomorphic location. The GIS analysis indicated only small differences in the slope gradient between open slope and gully landslide locations. However, as gullies appear to be significantly steeper in the field than open slopes this could indicate errors in the DEM. Since the

DEM is based on 25 m TRIM data, small steep areas can be lost within each pixel of the DEM.

Table 2.4: Mean and median GIS slope gradients by land use and geomorphic location. * C = clearcut, W = windthrow, N = natural and R = Road, **OS = open slope and G = gully

| *Land Use by **Geomorphic Location | n | % of Total Landslides | Mean Slope | Median Slope |
|---|---|---|---|---|
| **OSC** | 30 | 13 | 31 | 32 |
| **GC** | 29 | 12 | 31 | 32 |
| **OSW** | 33 | 14 | 33 | 33 |
| **GW** | 43 | 19 | 32 | 33 |
| **GN** | 19 | 8 | 28 | 30 |
| **R** | 79 | 34 | 29 | 29 |
| **Total** | 233 | 100 | | |

#### 2.4.1.3 Field Data Analysis

A comparison between terrain attributes and landslide dimensions was conducted for 24 clearcut and 24 windthrow associated open slope landslides. Wilcoxon tests showed that there was a significant difference (p=0.05) between the median failure slope (the measured slope of the failure surface in the initiation zone) angle for clearcuts and windthrow at 34˚ and 39˚, respectively (Table 2.5). There was a significant difference (p=0.05) between the median origin slope (the estimated slope of the original ground surface before failure occurred in the initiation zone) for clearcuts and windthrow at 36˚ and 41˚, respectively.

There is a significant difference (p= 0.001) in soil depth with a median depth of 1.2 m and 0.5 m for clearcuts and windthrow, respectively. There is a significant difference (p= 0.05) in rooting depths although the median depths were identical at 0.3 m. The mean rooting depths were 0.4 m and 0.3 for clearcuts and windthrow, respectively. The variability between the windthrow and clearcut associated landslides for failure slope gradient and soil depth are shown in the box plots (Figure 2.11).

Although not significant, landslide initiation zone width and area in clearcuts were generally smaller than in windthrow. Since soil depth was greater for clearcuts than windthrow, the initiation volume was greater for clearcuts, although it was not significant ($p>0.05$). Clearcut landslide runout length is significantly greater than for windthrow landslides.

Table 2.5: t-Tests for differences between field truthed clearcut and windthrow landslides. ***** C = clearcut **W = windthrow (ns: not significant - $p>0.05$; n = 48)

| **Dependent Variable** | **P-value** Wilcoxon | **Median Value** *C | ** W |
|---|---|---|---|
| Failure Slope ($^o$) | 0.013 | 34 | 39 |
| Origin Slope ($^o$) | 0.035 | 36 | 41 |
| Soil Depth (m) | 0.0005 | 1.2 | 0.5 |
| Elevation | ns | 435 | 506 |
| Rooting Depth (m) | 0.025 | 0.3 | 0.3 |
| Initiation Zone Width(m) | ns | 15 | 19 |
| Initiation Zone Length(m) | ns | 21 | 20 |
| Initiation Area ($m^2$) | ns | 300 | 400 |
| Initiation Volume ($m^3$) | ns | 367 | 260 |
| Total Runout Length (m) | 0.016 | 248 | 133 |
| Total Area ($m^2$) | 0.054 | 5404 | 2852 |

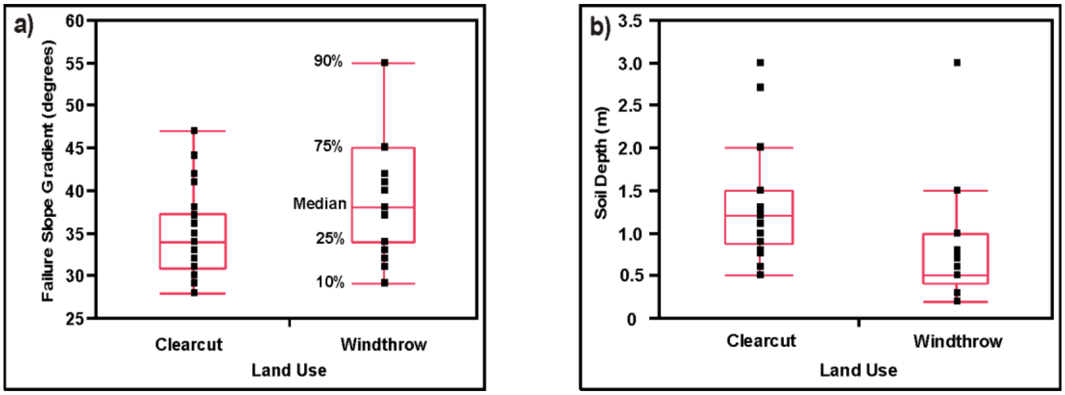



Figure 2.11: Box plots showing variability between clearcut and windthrow for a) failure slope gradient, b) soil depth. (n = 48)

Chi-Square or contingency tests were conducted to test significant differences between landslide attributes for clearcuts and windthrow (Table 2.6) and indicate terrain attributes that were characteristic for windthrow and clearcuts. Clearcut associated landslides are more likely than windthrow landslides to occur on concave, mid-slopes with poorly to imperfectly drained morainal soils between 0.5 and 1.5 m (median 1.2 m) deep (Figure 2.12 a, b, c, d, e and f). Clearcut landslides also typically occur on slopes between 30˚ and 40˚ whereas, windthrow landslides frequently occur on slopes between 40˚ and 45˚ (Table 2.5). Specifically, windthrow associated landslides are common on both convex and straight slopes with moderately well to well drained colluvial soils between 0 and 1 m deep  and situated at lower and upper slope positions (Figure 2.12 a, b, c, d, e and f). The initiation dimensions between clearcuts and windthrow were not significantly different.

Two multivariate statistical analyses were conducted using Chi-squared Automatic Interaction Detector (CHAID) and logistic regression to compare landslide sites with blowdown (windthrow) or landslide sites with no blowdown for the 48 field investigated landslides. The following independent variables were used in the analysis:

vertical and horizontal slope curvature, soil type, soil drainage, failure slope gradient, soil depth, rooting depth, and distance to clearcut edge. The CHAID and logistic regression analysis indicated that the two most significant variables between clearcut and windthrow associated landslides were soil depth and vertical slope curvature. A summary of this analysis is in Appendix A.

Table 2.6: Contingency tests for clearcut versus windthrow landslides. * chi-square suspect due to small cell count. (ns: not significant - p>0.1; n = 48)

| **Variable** | **Significance Level - Chi Square** | |
|---|---|---|
| | Pearson | Fisher's Exact |
| Slope Position | 0.023* | |
| Soil Type | 0.009 | 0.010 |
| Drainage Class | 0.042 | 0.040 |
| Vertical Curvature | 0.003 | |
| Horizontal Curvature | 0.054 | |
| Landslide Type | <0.0001 | <0.0001 |

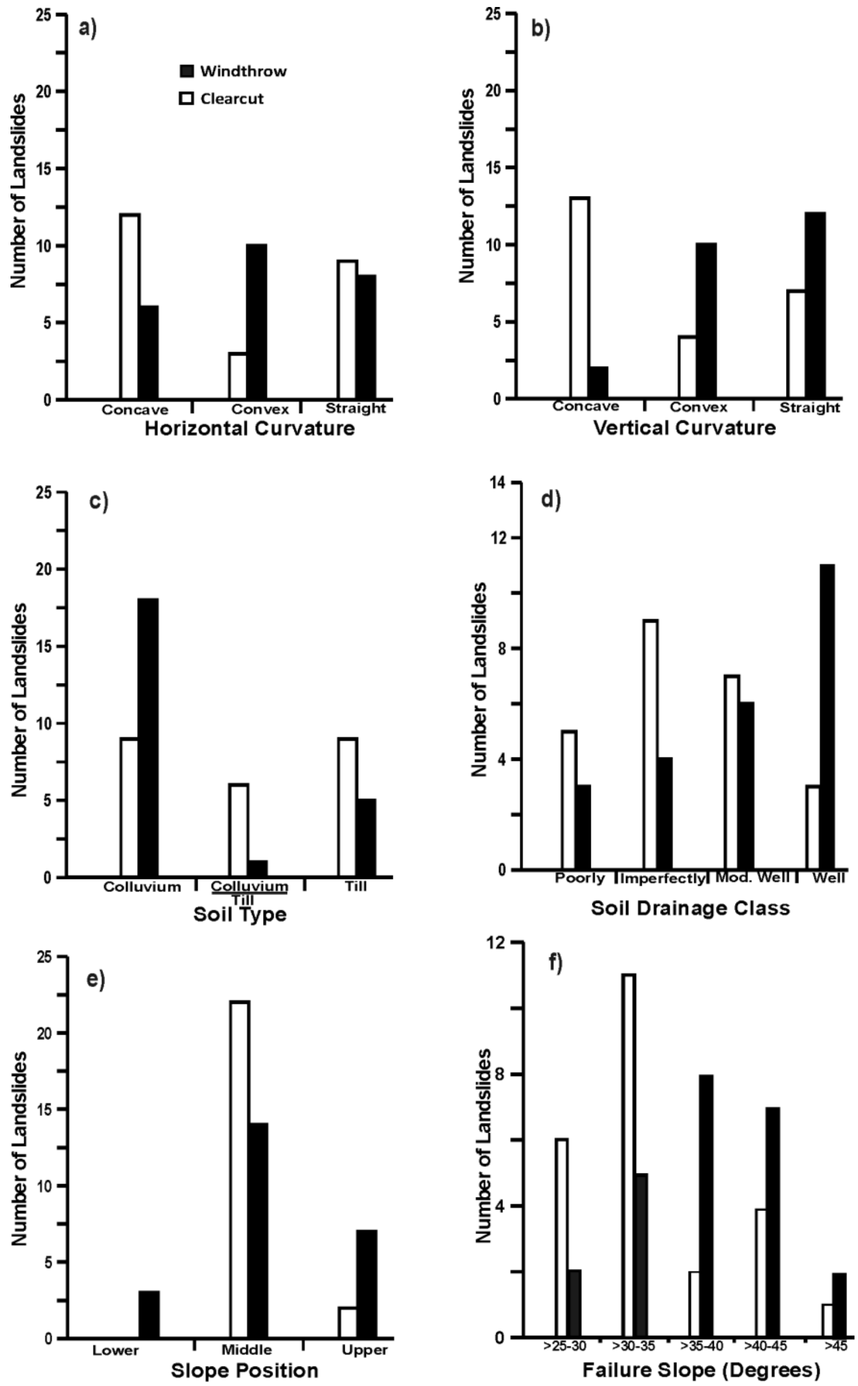



Figure 2.12: Histograms showing terrain attributes characteristic of clearcut and windthrow landslides: a) horizontal slope curvature, b) vertical slope curvature, c) soil type, d) soil drainage class, e) slope position, f) slope class. (n = 48)

### 2.4.2 Distribution of Landslide Locations

A landslide distribution analysis was undertaken using the GIS inventory for 233 landslides from the November 15, 2006 storm. The distance of landslides from the coastline, distance to the nearest clearcut edge, and slope aspect were determined for each landslide to better understand the factors causing landslides and windthrow. The distribution of precipitation was also determined using Environment Canada and MOFR weather station data to understand the orographic effects on landslide distribution and initiation. Windthrow associated landslides are generally clustered in specific areas and clearcut associated landslides are distributed more evenly throughout the landscape (Figure 2.12). Landslide distribution for some land uses appears to be related to proximity to the coastline, clearcuts and slope aspect.

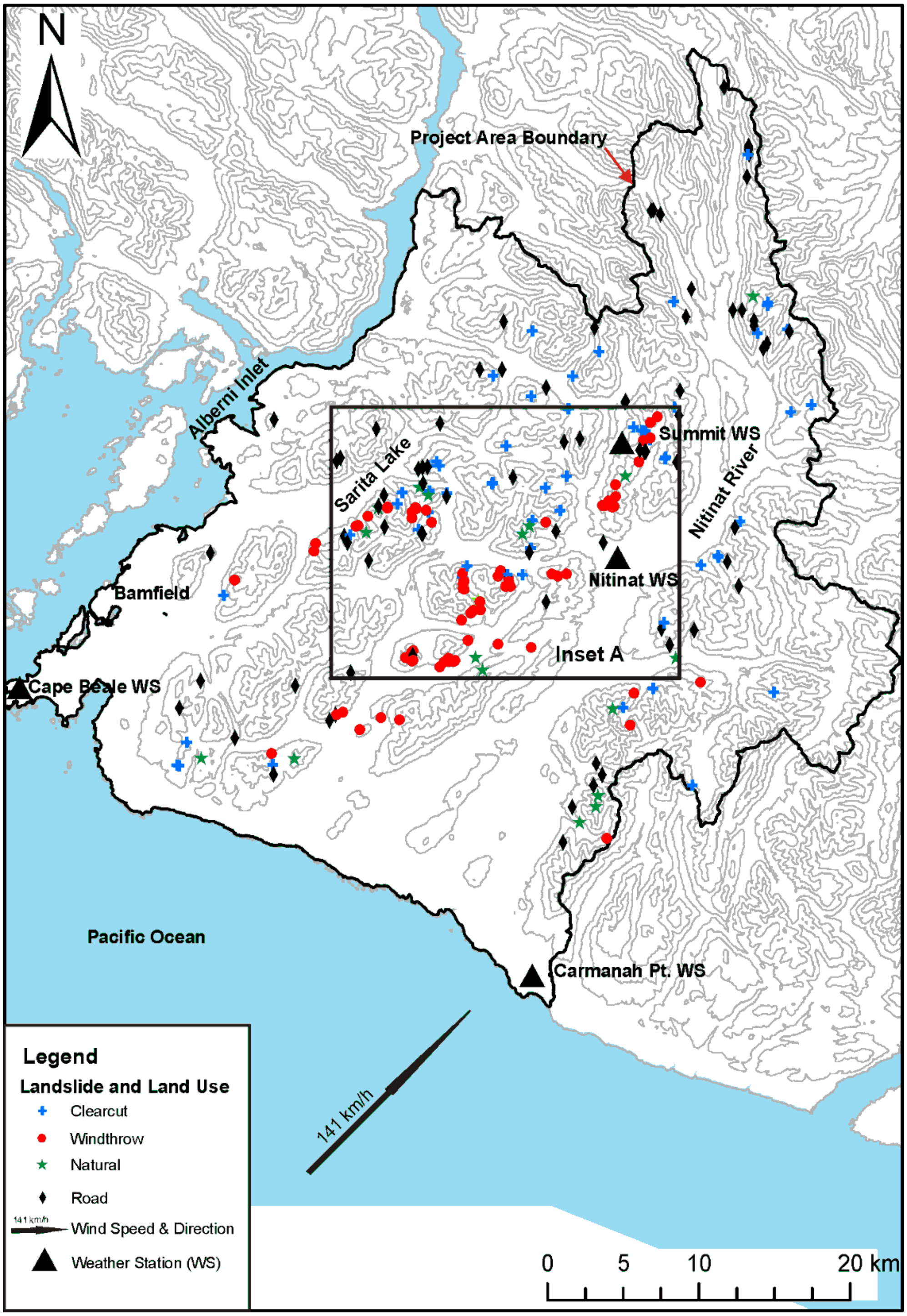



Figure 2.13: Distribution of landslides by land use. Inset A is shown in Figure 2.19. Three main clusters of landslides, a majority windthrow related, were identified. Dominant wind direction and speed from upper level soundings, elevation 1829 m, at Quillayute, WA, November 15, 2006 (12:00 PM), was from the southwest at 141 km/h (UOW, 2011).

The nearest distance to the open Pacific Ocean coastline was calculated from the landslides point of origin on the DEM (Figure 2.14). The majority (80%) of landslides occur between 12 and 36 km from the coastline. These distances are much greater than reported in a study by Jakob (2000) that was conducted in Clayoquot Sound approximately 150 km to the northwest. The reasons for this difference are unclear but could be due to differences in topography between the different areas, distribution of precipitation, or the relative locations of unlogged old growth adjacent to recent clearcuts. The Clayoquot Sound study is also adjacent to Strathcona Provinicial Park, which was not included in the study and likely affected the analysis (Jakob, 2000).

Windthrow patches and windthrow landslides appear to occur closer to the coastline than clearcut and road landslides (Figure 2.14). This could be due to higher wind speeds occurring near the ocean. The Estevan Coastal Plain occupies a narrow 5 kilometre wide strip along the coastline and consists of relatively gentle terrain with few opportunities for landslide initiation. Inland and eastward, the terrain becomes mountainous and steeper with more recent logging adjacent to unlogged old growth forest. The steeper terrain further eastward and the orographic effects caused by the mountains are likely the causes of a majority of the landslides that are occurring in these clusters. Unlogged old growth adjacent to clearcuts is more vulnerable to windthrow as shown by Mitchell et al. (2001).

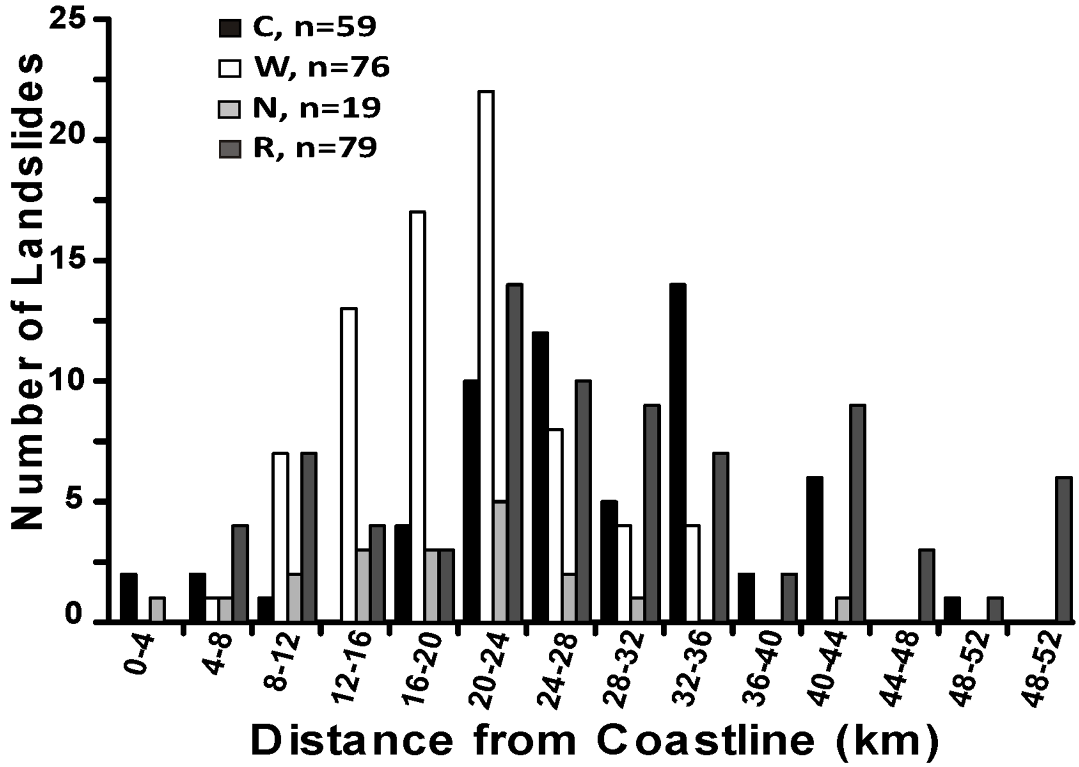



Figure 2.14: Distance to coastline by land use.

* C = clearcut, W = windthrow, N = natural and R = Road

The distance of landslides from the coast versus elevation was used in conjunction with weather station locations to understand the orographic effects of the storm event (van Zeyl, 2009). With windthrow and clearcut landslides plotted relative to their elevation and distance from the coast, no real trend is evident (Figure 2.15). However, the graph indicates some clustering of windthrow landslides between an elevation of 500 m and 700 m. This clustering of windthrow landslides could be due to several factors such as the freezing elevation before and after the November 15 storm, vicinity of adjacent clearcuts, steep terrain, and windthrow patches.

Windthrow associated landslides are closely related to wind direction. The dominant wind directions for the November 15, 2006 storm were from the south and southeast and windthrow landslides were predominantly oriented to the southeast (windward slope) and northwest (leeward slope) (Figure 2.16). Historical wind measurements at Cape Beale are also consistent with dominant wind directions during winter months from the southeast (Environment Canada, 2009a).

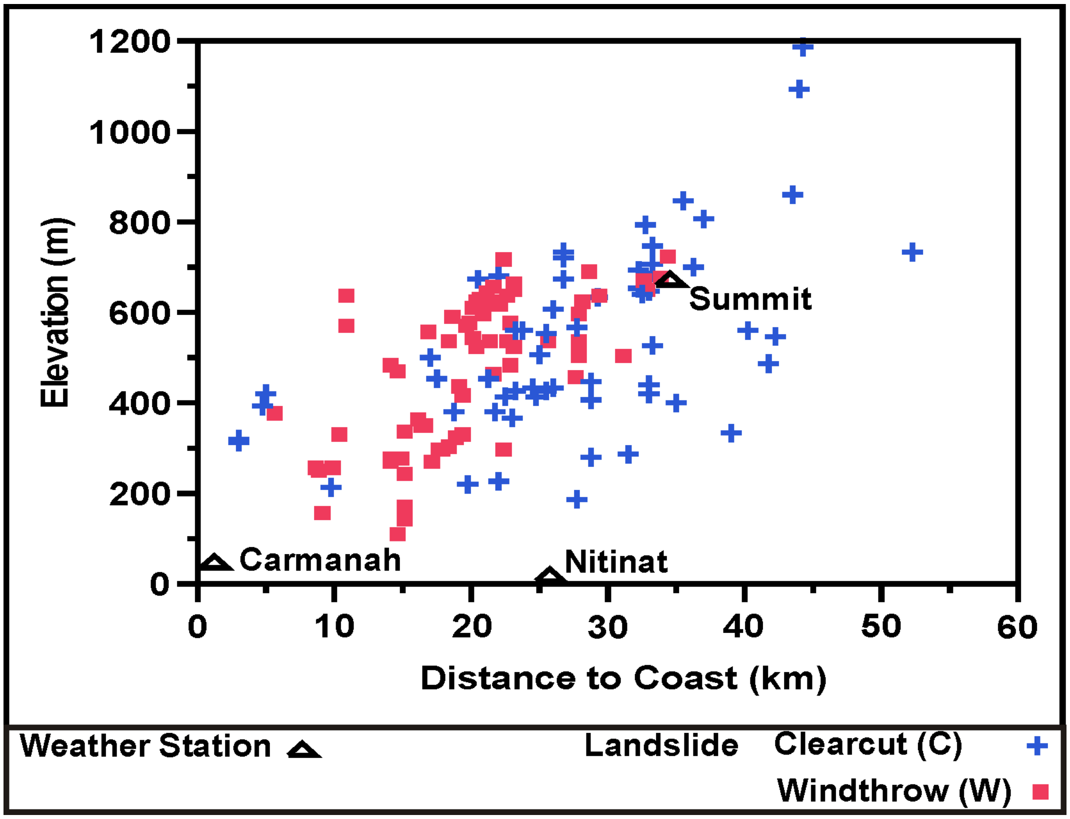



Figure 2.15: Distance from the coast versus elevation of landslides for windthrow and clearcut associated landslides. (n = 135)

The presence of windthrow landslides on leeward slopes could be due to wind turbulence after the winds have blown over the windward side of the slope (Stathers et al., 1994; Everham and Brokaw, 1996). Since the windthrow is preferentially dominant on south aspects due to maximum wind pressures occurring on slopes perpendicular to wind direction, there is a trend for windthrow landslides to also occur on these slopes. Clearcuts are harvested on all slopes irrespective of slope aspect however; there is also a dominant slope aspect for these landslides on east-southeast aspects. In addition, there are no single slope aspect octants that are dominant throughout the project area regardless of land use. GIS was used to determine the total area within each slope aspect octant for the entire project area. Each of the eight slope aspect octants represented between 8% and 12% of the total project area.

The land use for each windthrow patch was identified with GIS as old growth, old growth reserve, second growth, second growth reserve, or park. For this project, second growth was defined as clearcuts that are at greater than 15 years old with advanced regeneration. There was no windthrow in any second growth stands less than 35 years old. Reserves were defined as forested areas within clearcuts that were either small groups of trees or narrow leave strips. Seventy-six landslides (100%) of windthrow associated landslides and 96% of the windthrow area occurred in old growth or old growth reserves (Table 2.7).

Second growth and second growth reserves accounted for only 4% of the total windthrow area. One percent of the total windthrow area was observed in Pacific Rim National Park. A majority (88%) of the windthrow area was adjacent to clearcuts <10 years old. The presence of a majority of windthrow within old growth and old growth reserves adjacent to clearcuts <10 years old likely indicates that windthrow occurrence is related to clearcut presence. It should also be noted that the percentage of clearcut edge adjacent to old growth and second growth stands was not calculated for this project. It appears that more old growth clearcut edge is resulting in more old growth windthrow.

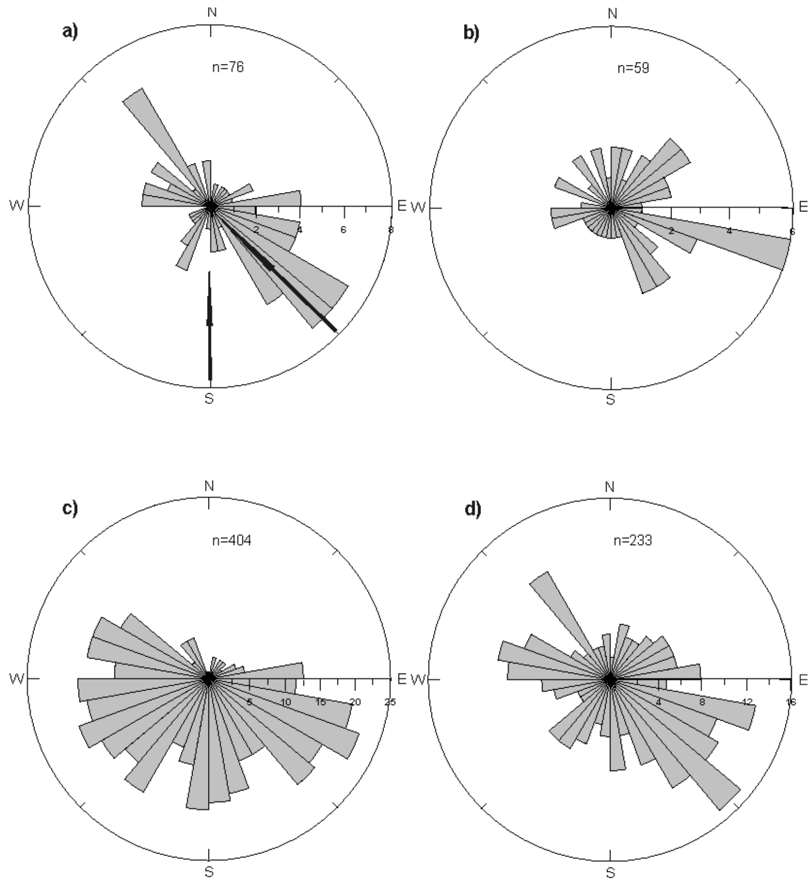



Figure 2.16: Slope aspects for: a) windthrow landslides, b) clearcut landslides, c) average aspect of 404 windthrow patches with or without landslides, d) all landslides. Black arrows in a) indicate dominant near surface wind directions for 96-hour period (November 14 to 17, 2006) at MOFR Summit weather station.

Table 2.7: Harvest age adjacent to windthrow polygon and number of landslides for each land use. *SG = second growth, SGR = second growth reserve, OG = old growth and OGR = old growth reserve

| *Land Use | # of Patches (% of Total Area) | Adjacent Harvest Age | | | | | # of LS |
|---|---|---|---|---|---|---|---|
| | | Old Growth | >0-10 years | >10-20 years | >20-30 years | >30 years | |
| SG | 18 (3%) | 0 | 12 | 1 | 0 | 5 | 0 |
| SGR | 16 (1%) | 0 | 15 | 0 | 0 | 1 | 0 |
| OG | 194 (61%) | 13 | 157 | 17 | 2 | 5 | 50 |
| OGR | 166 (34%) | 0 | 164 | 2 | 0 | 0 | 26 |
| Park | 10 (1%) | 10 | 0 | 0 | 0 | 0 | 0 |
| Total # (% Area) | 404 (100%) | 23 (4%) | 348 (88%) | 20 (5%) | 2 (<1%) | 11 (3%) | 76 |

Windthrow patches occur at different elevations and slope angles for different land uses (Table 2.8). The second growth and second growth reserve windthrow areas occur on gentler slope angles and at lower elevations, which is why fewer landslides are occurring in second growth. The old growth and old growth reserves are characterized by terrain on steeper slopes and at higher elevations. The occurrence of windthrow landslides adjacent to younger clearcuts is related to their location on these steeper slopes and higher elevations.

The old growth and second growth reserves are also smaller on average than second growth and old growth forests. The small relative size of the reserves is a function of their limited areal extent within clearcut boundaries.

Table 2.8: Attributes for windthrow patches with mean values from GIS analysis. *SG = second growth, SGR = second growth reserve, OG = old growth and OGR = old growth reserve

| *Land Use | % of Patches | Mean Area (m2) | Mean Elevation (m) | Mean Slope (°) |
|---|---|---|---|---|
| **SG** | 4 | 32500 | 159 | 13 |
| **SGR** | 4 | 11900 | 257 | 21 |
| **OG** | 48 | 56900 | 465 | 26 |
| **OGR** | 41 | 37500 | 368 | 19 |
| **Park** | 3 | 21100 | 39 | 6 |

The relationship between windthrow landslides and distance to the clearcut edge was observed in the field and analysed using GIS (Figure 2.17). The distance was measured between the landslide initiation point on the DEM and the distance to the nearest clearcut edge for windthrow-associated landslides. The direction of the windthrow could not be determined from the satellite imagery therefore, the distance to the clearcut edge may be on the windward or leeward side of the clearcut. Distances were classified into 10 m intervals. A majority, 54 out of 76 (71%), of the windthrow landslides, were within 70 m of a clearcut edge. Windthrow landslides within 10 m and 20 m of the clearcut edge accounted for 17 (22%) and 28 (39%) of the landslides, respectively.

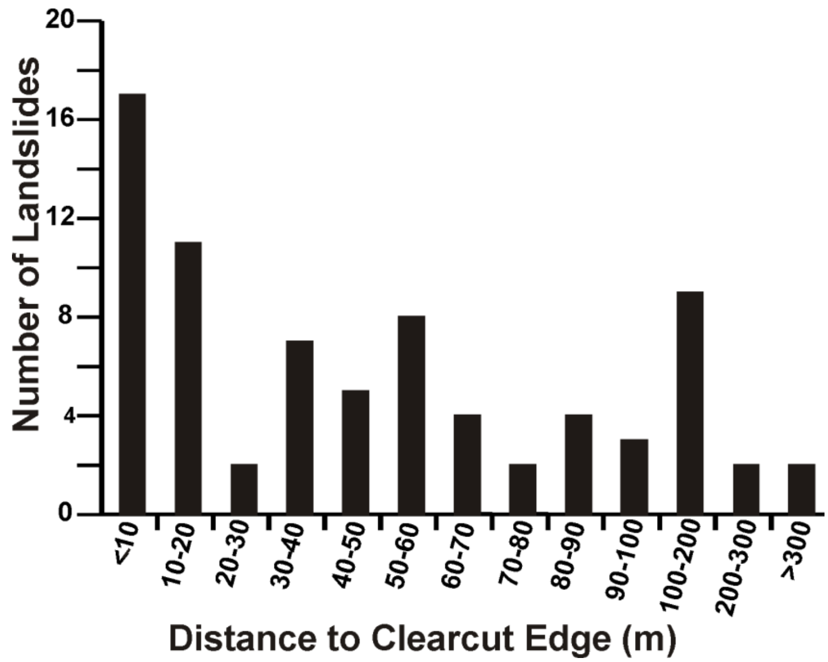



Figure 2.17: Windthrow landslide initiation distance from the clearcut edge. Note: For distances greater than 100 m from a clearcut edge, each category is in 100 m intervals. (n = 76)

The clearcut harvest age adjacent to windthrow landslides was analysed using GIS with digital forest cover information (Figure 2.18). The results show that 11%, 53% and 88% of windthrow associated landslides occurred adjacent to clearcuts ≤1 year old, ≤3 years old and ≤10 years old, respectively. The location of windthrow landslides adjacent to clearcuts ≤10 years old is similar to windthrow patches and clearcut adjacency. This is significant evidence that the younger the adjacent clearcut harvest age the more likely there will be windthrow and subsequent windthrow landslides. This phenomenon is likely due to wind firmness along the clearcut boundaries, roughness or irregularity of the clearcut boundary and roughness of the second growth canopy adjacent to old growth forest. Older clearcuts have been subjected to previous, less severe storms, allowing wind firmness and irregularities to develop along the cutblock boundaries; younger clearcut edges have not developed wind firmness (Stathers et al., 1994; Cucchi et al., 2004). The lower percentage of landslides adjacent to clearcuts less than one year old, with respect to two and three year old clearcuts, could be due to the relative proportion of clearcut area within each of these age categories. The percentage of windthrow landslides adjacent to clearcuts regarding harvest age is not weighted with respect to the area of clearcut within each harvest age category.

Three main clusters of landslides were identified within the project area (Figure 2.19). A kernel density method, an ArcGIS extension, was used to show the areas with high landslide densities. A similar method was used by Guthrie and Evans (2004) to analyse the distribution of landslides on northern Vancouver Island. In the current study, 54% of the landslides within these clusters were associated with windthrow, whereas only 5%, 19%, and 22% were associated with natural, road, and clearcut, respectively.

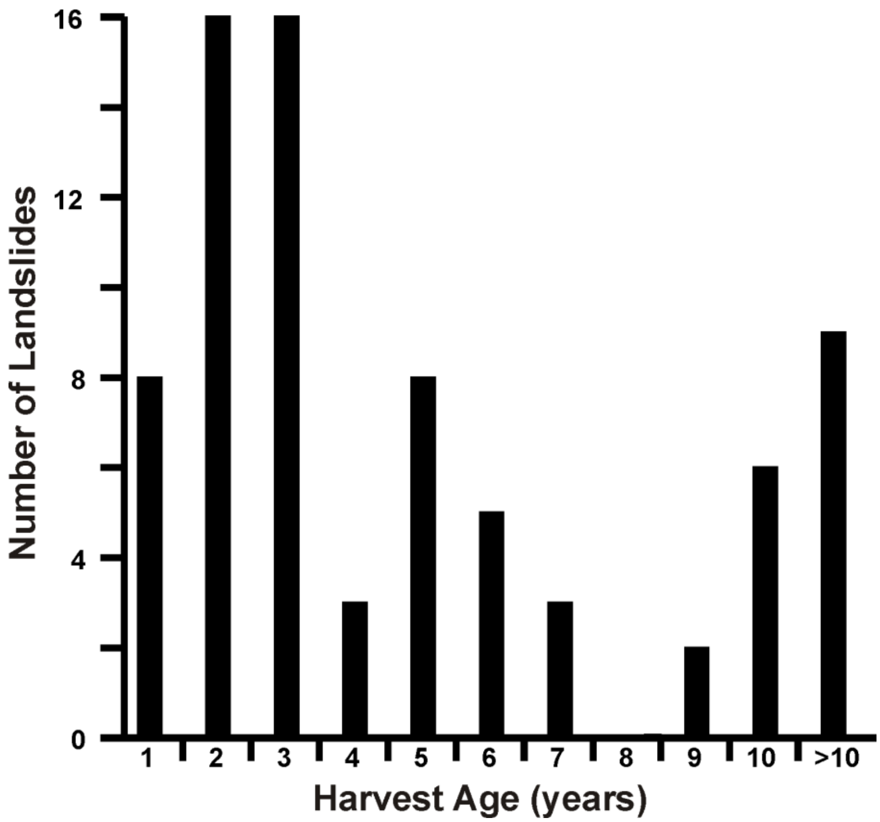



Figure 2.18: Harvest age of clearcuts adjacent to windthrow associated landslides. (n = 76)

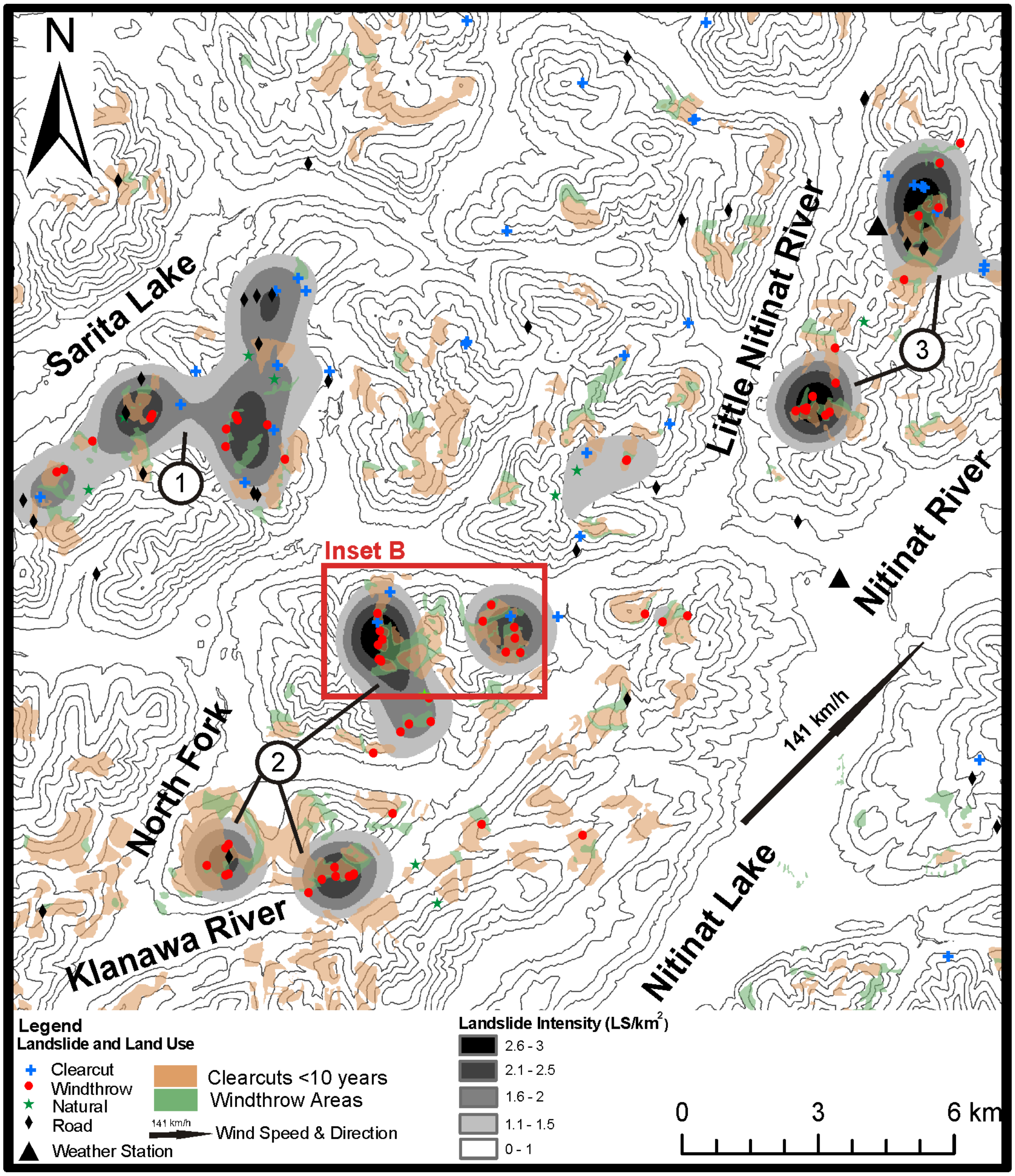



Figure 2.19: Windthrow landslide clustering (Inset A): windthrow landslides are clustering primarily adjacent to clearcuts (brown polygons). The kernel density method, an ArcGIS extension, using nearest neighbour analysis shows a maximum landslide density of 3 LS/km$^2$, which consists mostly of windthrow landslides. Inset B indicates area with detailed windthrow and landslide analysis. Dominant wind direction and speed from upper level soundings, elevation 1829 m, at Quillayute, WA, November 15, 2006 (12:00 PM), was from the southwest at 141 km/h (UOW, 2011).

The junction of the Klanawa River and North Fork of the Klanawa River (Inset B) is an example of an area where the majority of windthrow landslides occurred adjacent to clearcut boundaries (Figure 2.20, Figure 2.21). This area demonstrates the impact of wind along clearcut boundaries and how the landslides cluster in localized areas. There were thirteen windthrow and three clearcut landslides. The key attributes for this area consisted of recent clearcuts, steep terrain, three helicopter clearcuts (possibly indicating unstable and/or isolated terrain), and extensive old growth forest.

The change detection identified eight landslides in Figure 2.20. A total of 4 landslides were identified as clearcut but were in windthrow patches. One landslide was correctly designated as within a clearcut and three landslides were identified as natural but were actually in windthrow patches. The field truthed/orthophoto data base classified 16 landslides within this area. Three landslides were in clearcuts and 13 were in windthrow patches.  Approximately 50% of the windthrow was identified incorrectly as clearcut by the change detection within this area (Figure 2.20).

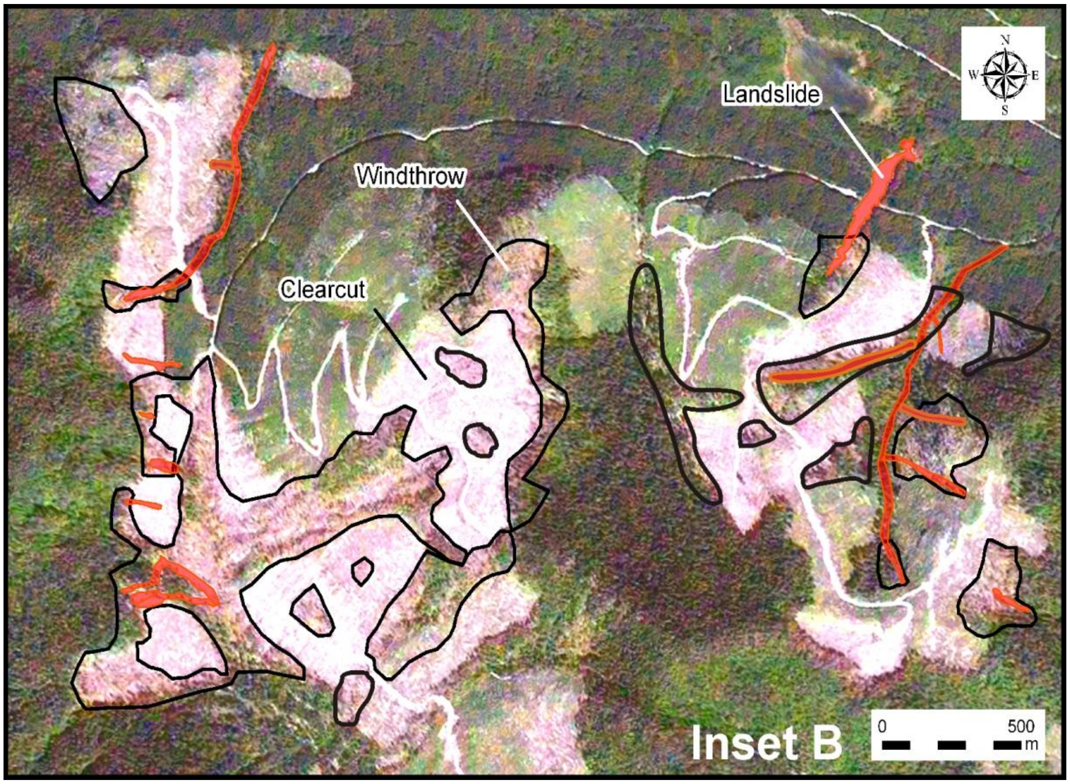



Figure 2.20: Clusters of windthrow landslides shown in Klanawa River and North Fork area (Inset B from Figure 2-19). Red polygons show runout zones for 16 landslides. SPOT 2007 satellite imagery used in conjunction with field truthing for this study to identify landslides, windthrow and clearcuts. SPOT 2007 imagery was also used for automated change detection analysis completed by Caslys Consulting for MOE.

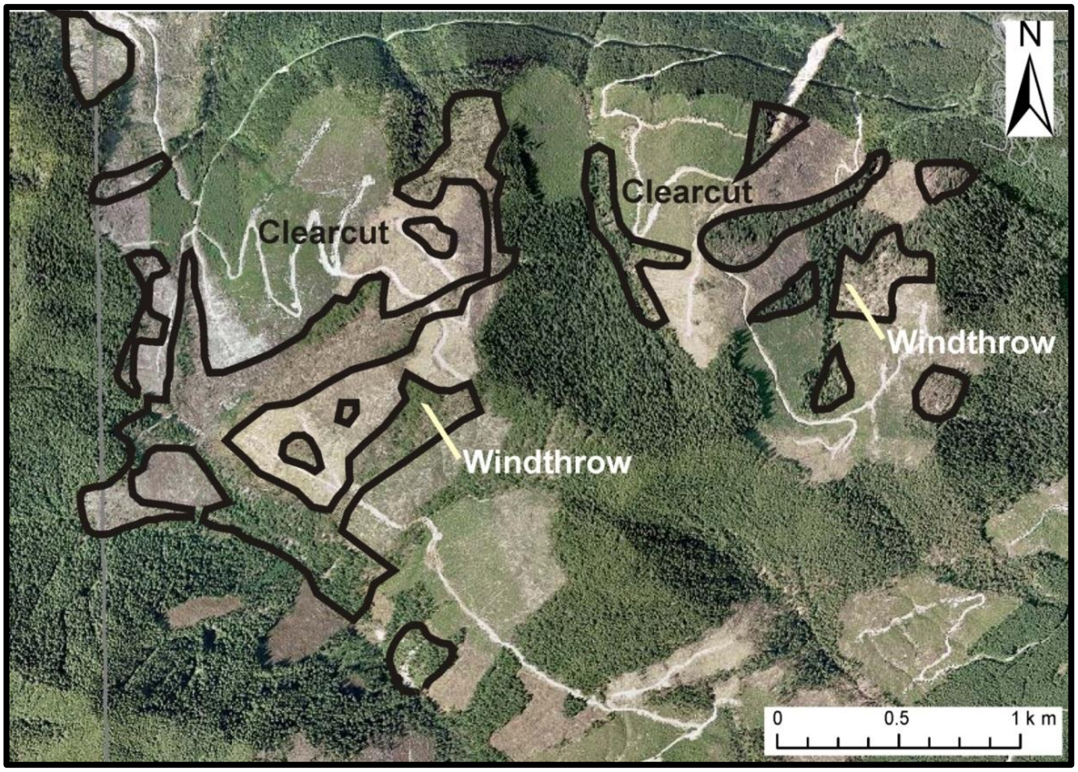



Figure 2.21: Clusters of windthrow analyzed in Inset B from Figure 2.20. This image illustrates how high resolution (0.3 m) orthophoto imagery from WFP was utilized to improved the identification of windthrow, clearcuts and landslides compared to using only lower resolution (2.5 m) SPOT 2007 satellite imagery.

Another area with a large concentration of landslides was near the Summit Weather Station, labelled as Cluster 3 (Figure 2.19, Figure 2.22). Six windthrow landslides were identified in this cluster with two on open slopes and four in gullied terrain. The higher resolution orthophoto imagery combined with field truthing allowed a more detailed analysis of the impacts of windthrow on landslide initiation compared to using automated change detection and SPOT satellite imagery.

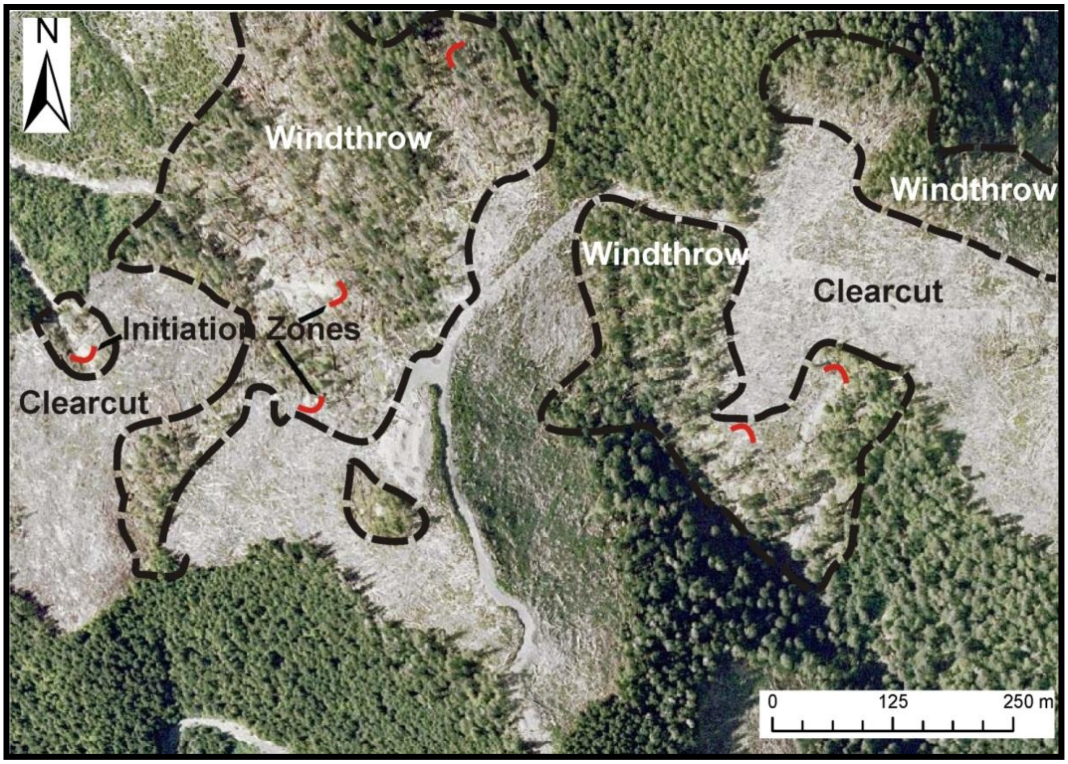



Figure 2.22: Cluster of windthrow associated landslides near Summit Weather Station identified with high resolution orthophoto imagery from WFP.

### 2.4.3 Landslide Density

The total landslide area and density was calculated for TFL 44, which accounts for 72% of the study area. The area was chosen for its complete and relatively up to date forest cover information and the fact it contained 179 of the 233 landslides identified for the entire study area. The land use areas were calculated using the TFL boundaries updated as of the year 2000 and harvest information updated to 1997 (Table 2.9).The total area within TFL 44 is 1097 $km^2$ with 46 $km^2$ and 502 $km^2$ excluded from the landslide density calculation as non-productive (NP) and slopes less than 20˚, respectively. The clearcut associated landslide density was divided into two age categories: clearcuts ≤15 years old and clearcuts >15 years old. Pacific Rim National Park, private land, TFL 46 and other forest licences were also excluded from the landslide density since forest cover data was not obtained and/or available for these areas.

Table 2.9: Landslide densities and percentage of area affected by landslides for TFL 44.

| | C (≤ 15 years) | C (> 15 years) | R | Logged | W | N | Unlogged | Total |
|---|---|---|---|---|---|---|---|---|
| **Number of landslides** | 28 | 17 | 51 | 45 | 72 | 11 | 83 | 179 |
| **% of landslides** | 16 | 9 | 28 | 25 | 40 | 6 | 46 | 100 |
| **Total landslide area ($km^2$)** | 0.3 | 0.2 | 0.4 | 0.5 | 1.2 | 0.2 | 1.4 | 2.3 |
| **Land use area ($km^2$)** | 113.9 | 186.4 | N/A | 300.3 | 11.7 | 237.0 | 248.7 | 549.1 |
| **% of total area** | 20.7 | 34 | N/A | 54.7 | 2.1 | 43.2 | 45.3 | 100 |
| **% of area affected by landsliding** | 0.3 | 0.1 | N/A | 0.4 | 9.9 | 0.1 | 10 | 10.1 |
| **Landslide density ($LS/km^2$)** | 0.25 | 0.09 | N/A | 0.15 | 6.15 | 0.05 | 0.33 | 0.33 |

*****Logged = the total for all clearcut landslides.

**Unlogged = the combined total for windthrow and natural landslides.

(C = clearcut, W = windthrow, N = natural and R = Road)

The November 15, 2006 storm caused approximately 11.7 $km^2$ of windthrow throughout the TFL and initiated 72 windthrow associated landslides in old growth forests with a majority adjacent to clearcuts. Approximately 4% of the total windthrow area was located in second growth between 40 and 70 years old but no landslides were observed in these windthrow patches. The remaining 96% of windthrow was within old growth forests where all 72 windthrow landslides occurred.

The landslide density for windthrow polygons was 6.15 landslides/ $km^2$. The windthrow landslide density was 25 times that of clearcut terrain and 123 times the natural rate. If the windthrow and natural landslides are combined as unlogged landslides, the “unlogged” landslide density is 0.33 landslides/$km^2$ compared to 0.25 landslides/$km^2$ for the clearcut (≤15 years old) landslide density. However, the association of windthrow adjacent to cutblock boundaries indicates that logging is influencing some or most of these windthrow landslides as without the clearcut, the windthrow may not have occurred. Consequently, if clearcut (≤15 years old) and windthrow landslide densities are combined, the landslide density is 0.54 landsides/km$^2$, which is 10.8 times the “natural” landslide density.

The clearcut landslide density was highest for clearcuts ≤15 years old and lowest for clearcuts >15 years old. The lower landslide density within second growth indicates that the steeper and more sensitive sites have probably already failed whereas the sensitive sites within the younger clearcut age classes are failing and resulting in a higher landslide density (Table 2.9).

The landslide area was analysed for 233 landslides with respect to each land use (Figure 2.23). It is common practice to select 500 m$^2$ as a minimum landslide area for analysis to ensure all landslides are identified in areas of partial green-up (Millard et al., 2002; Brardinoni et al., 2003). There was no minimum landslide area for this project consequently; there were four landslides with areas less than 500 m$^2$. These four landslides had areas between 400 and 481 m$^2$ and because of the high resolution orthophoto imagery and field truthing, the author is confident that all landslides were identified. The mean landslide size is 12,471 m$^2$ and the median size is 4544 m$^2$. Mean and median landslide areas are comparable to those of Guthrie and Evans (2004) and Wolter et al. (2010). A majority (90%) of landslides are ≤30,000 m$^2$ and 72% are ≤10,000 m$^2$ in size. Windthrow associated landslides tend to dominate the larger landslide classes whereas roads and clearcuts are more restricted to between the 2000 and 20,000 m$^2$ classes. The mean windthrow and natural associated landslide areas are larger than the clearcut and road landslides (Table 2.10). There were similar results for landslide length where clearcut locations resulted in shorter landslides.

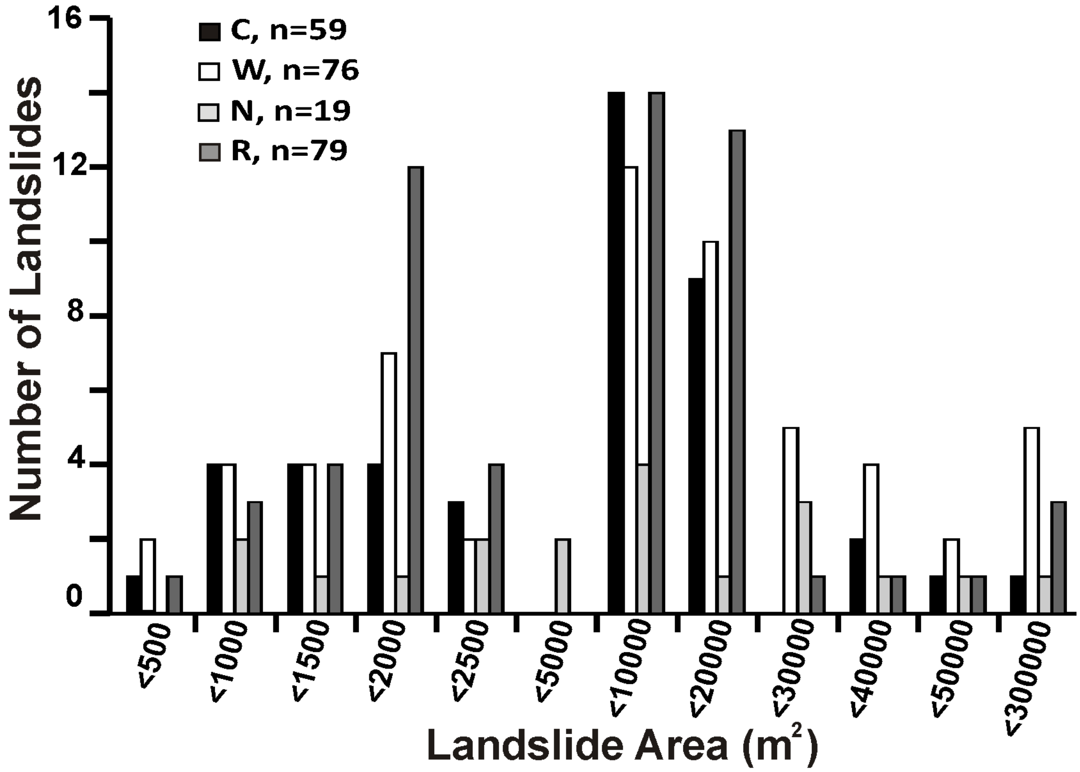



Figure 2.23: Landslide area by land use (surface area projection).
*C = clearcut, W = windthrow, N = natural and R = Road

Table 2.10: Landslide dimensions and type for the entire project area. *C = clearcut, W = windthrow, N = natural and R = Road (DF – debris flow, DS – debris slide)

| *Land Use | n | LS Area ($m^2$) | | Total LS Area ($km^2$) | LS Length ($m^2$) | | LS Type | | % Impact Stream |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Median | | Mean | Median | %DF | %DS | |
| C | 59 | 10144 | 4313 | 0.598 | 439 | 273 | 100 | 0 | 69 |
| W | 76 | 17913 | 5351 | 1.361 | 619 | 273 | 74 | 26 | 66 |
| N | 19 | 14654 | 5987 | 0.278 | 651 | 377 | 100 | 0 | 79 |
| R | 79 | 8448 | 3883 | 0.667 | 413 | 213 | 92 | 8 | 62 |

## 2.5 Comparing GIS Techniques for Landslide and Windthrow Analysis

Two methods were used to analyse the impacts of landslides and windthrow in the project area. Initially, change detection was conducted by the MOE by comparing SPOT satellite imagery from 2007 after the winter 2006/2007 storm event to previous SPOT imagery obtained from 2004 and 2006 (Caslys Consulting, 2007). New landslides, windthrow, roads, and clearcuts were identified for a majority of Vancouver Island including the project area. Some field checking was conducted in conjunction with the change detection (Forest Practices Board, 2009).

The combination of change detection and manual identification using landslide event reports, field truthing and satellite imagery enabled a more complete analysis of the impacts of windthrow and weather on landslide initiation on southwestern Vancouver Island. In total, 233 landslides were identified within the project area compared to 129 using only automated change detection. Based on an analysis of the GIS shape files from Caslys Consulting, large tracts of windthrow were not identified with the automated change detection method. The major problem with identifying windthrow patches using change detection was that large patches of windthrow appeared similar to fresh clearcuts. Small windthrow patches around clearcut edges were difficult to distinguish as windthrow from the surrounding forest and clearcuts. More field truthing is necessary to distinguish between clearcuts and windthrow when using change detection. Our analysis identified 76 windthrow related landslides and 404 windthrow patches. The change detection only identified six windthrow landslides and 91 windthrow patches. An additional 14 landslides were incorrectly identified as clearcut landslides by automated change detection although they were located in windthrow patches. The increased identification of landslides and windthrow during this project is a result of field truthing during the summer 2007, as well as the use of landslide reports, 0.3 m resolution orthophoto imagery, and helicopter/vehicle reconnaissance maps obtained from WFP. Thus, extreme caution and thorough field truthing should be conducted when analyzing landslide density with automated systems such as change detection.

## *2.6* Discussion

According to previous studies, clearcut landslides are more frequent than natural landslides (Jakob, 2000; Guthrie, 2002; Rollerson et al., 2002; Wolter et al., 2010). However, after the November 15, 2006 storm event the windthrow landslide density was 25 times higher than the clearcut (≤15 years old) landslide density and 123 times higher than the "natural" landslide density. This could be due to several factors such as the effects of soil and terrain attributes, the existence of recent clearcuts, the influence of climate and weather patterns, topography, or changes in root strength and forest hydrology.

### 2.6.1 Soil and Terrain Attributes

Previous studies have focussed on how logging, terrain attributes, and weather patterns affect the location of windthrow (Ruel et al., 2002; Tang et al., 1997). The collection of field data on landslide attributes allows a detailed analysis of the important variables involved in slope failures. The null hypothesis is that clearcut and windthrow related landslides occur on similar terrain with no significant differences. However, this research indicated a significant difference between slope gradient, slope shape and soil thickness. Thus, the alternative hypothesis holds true: clearcut and windthrow landslide initiate on different terrain. These differences in terrain attributes may result from:

1. Windthrow landslides require steeper slopes with thinner soils to initiate since these slopes are partially reinforced by root systems that have not decayed from previous harvesting; or
2. Windthrow landslides occur around the perimeter of clearcuts where the slopes are steep and the soils are thinner and more similar to inoperable terrain with poor quality trees. The clearcut boundaries are commonly

located along operability lines with poor quality trees located on the outside of the clearcut boundary, which may be more vulnerable to windthrow.

However, no significant differences in terrain attributes were observed using the GIS analysis. In particular, the GIS slope gradients were significantly lower than the field measurements. This could be related to errors in the DEM causing a higher standard deviation than the field truthed database. The differences in field and GIS results is strong evidence that field truthing during landslide studies is critical to an accurate landslide analysis.

### 2.6.2 Distribution of Windthrow and Landslides

Windthrow landslides were observed within three main clusters and were influenced by factors such as topography, wind direction and speed, isolated intense storm cells, valley orientation, and timber harvesting. The topography associated with the windthrow landslide clusters is characterized by steep mountainous terrain located east of the Estevan Coastal Plain (Figure 2.19). The steep terrain within the windthrow clusters was more severely impacted by oncoming storms than gentler slopes along the coastal plain and valley bottoms because of orographic effects and wind direction (Stathers et al., 1994). During fall and winter storm events, moist Pacific air cools rapidly as it rises over the mountainous terrain (Loukas and Quick, 1994). This causes the storm clouds to release the moisture stored in them resulting in rain and/or snow. In addition, isolated cells of intense precipitation can also be present during storms and are commonly related to orographic uplift (Roe, 2005; Guthrie and Evans, 2004). The isolated cells of intense precipitation are difficult to analyse since they are not detected by the widely spaced weather stations (Guthrie et al., 2010; Miles et al., 2008).

Wind direction and slope aspect are also closely correlated to windthrow landslides and windthrow patches. A majority of windthrow landslides are on slope aspects between east and south, which is similar to the dominant near surface wind direction from the southeast for the November 15 storm. The southeast slopes will also experience increased total rainfall due to their windward position compared to leeward slopes. The increased precipitation appears to result in a large number of landslides occurring on windward slopes. In addition, dominant south to southeast winds exert high wind pressures on these slope aspects, therefore resulting in windthrow and landslides. The high winds on the southeast slopes intensify the impact of the rain by driving precipitation into the soil (Guthrie et al., 2010).

Valley orientation is another factor involved in the clustering of landslides. The clusters of landslides tend to occur near the junctions of river valleys such as the Little Nitinat and Nitinat River, the Klanawa and North Fork of the Klanawa River, and the Sarita River with its major tributaries (Figure 2.19). The river junctions tend to consist of areas inland where there is steeper, high elevation terrain, recent logging, and extensive areas of unlogged old growth. As the wind moves up the main valleys, its abrupt impact on slopes at valley junctions can result in large patches of windthrow (Stathers et al., 1994).

The windthrow landslides are primarily located adjacent to clearcuts. The presence of windthrow landslides adjacent to clearcuts could be due to several factors such as harvest age, previous windthrow, and terrain attributes. The old growth forest adjacent to younger clearcuts (≤10 years old) are impacted by wind more than older clearcuts since the surrounding forests have not been exposed to a large number of windstorms. Previous windstorms gradually allow the root systems of trees to develop lateral shear resistance and therefore build up wind firmness (Rowan et al., 2003). The majority of windthrow patches and windthrow landslides adjacent to clearcuts ≤10 years old supports this hypothesis.

Terrain adjacent to clearcuts is possibly inoperable and steeper than inside the clearcuts. Terrain attributes such as steep slopes, thin soil, convex slope shape, well-drained soils, and shallow rooting systems are a major factor in the presence of windthrow areas adjacent to clearcuts. Since a majority of gentle slopes were in second growth and these stands were logged first, most slopes remaining for timber harvesting over the past 10 years have been steeper, less stable slopes. Consequently, the recent clearcuts are also surrounded by steeper less stable terrain that is more vulnerable to landslide initiation. The edges of younger clearcuts, surrounded by unlogged old growth, on steep slopes are more vulnerable to wind storm events resulting in windthrow and landslides.

### 2.6.3 Landslide Density

The windthrow landslide density was higher than the clearcut landslide density. Previous studies such as Howes (1987), Jakob (2000), Guthrie (2002), and Wolter et al. (2010) have found clearcut landslide densities to be 2 to 9 times higher than natural rates. This study has determined that there were 25 times as many landslides in windthrow areas than clearcuts. The clearcut landslide density (≤15 years) was 5 times the natural landslide density. However, if windthrow landslides are considered logging related then the logged landslide density (clearcut ≤15 years + windthrow) is 10.8 times the ‘natural’ landslide density, which is similar to other studies. However, landslide densities for previous studies such as Jakob (2000), Wolter et al. (2010) and Rollerson et al. (1998, 2002) are based on landslide density calculations for several years (eg. 5 to 15 years) of landslide activity whereas, the landslide density for this project was based on one winter storm season.

### 2.6.4 Windthrow Effects on Landslide Initiation

Observations during field data collection indicated multiple ways that windthrow facilitates landslide initiation, such as disturbance of surface water flow, exposure of mineral soil, loss of forest canopy, loss of root reinforcement, dislodgement of soil and/or rock, and the movement of trees and root systems. Disturbed surface water flows and exposed mineral soil are related and occur when windthrow overturns the roots of trees leaving a hole in the forest floor and exposing the mineral soil. This hole enables the catchment and storage of water from rainstorms, and facilitates its entry into the soil subsurface. If several trees are overturned adjacent to one another, storm water can accumulate and then be diverted across the hill slope (Figure 2.24). The diverting of normal surface flow patterns concentrates water in one area can lead to excess pore water pressures (Buchanan and Savigny, 1990). This phenomenon was observed at five landslide locations during field data collection.

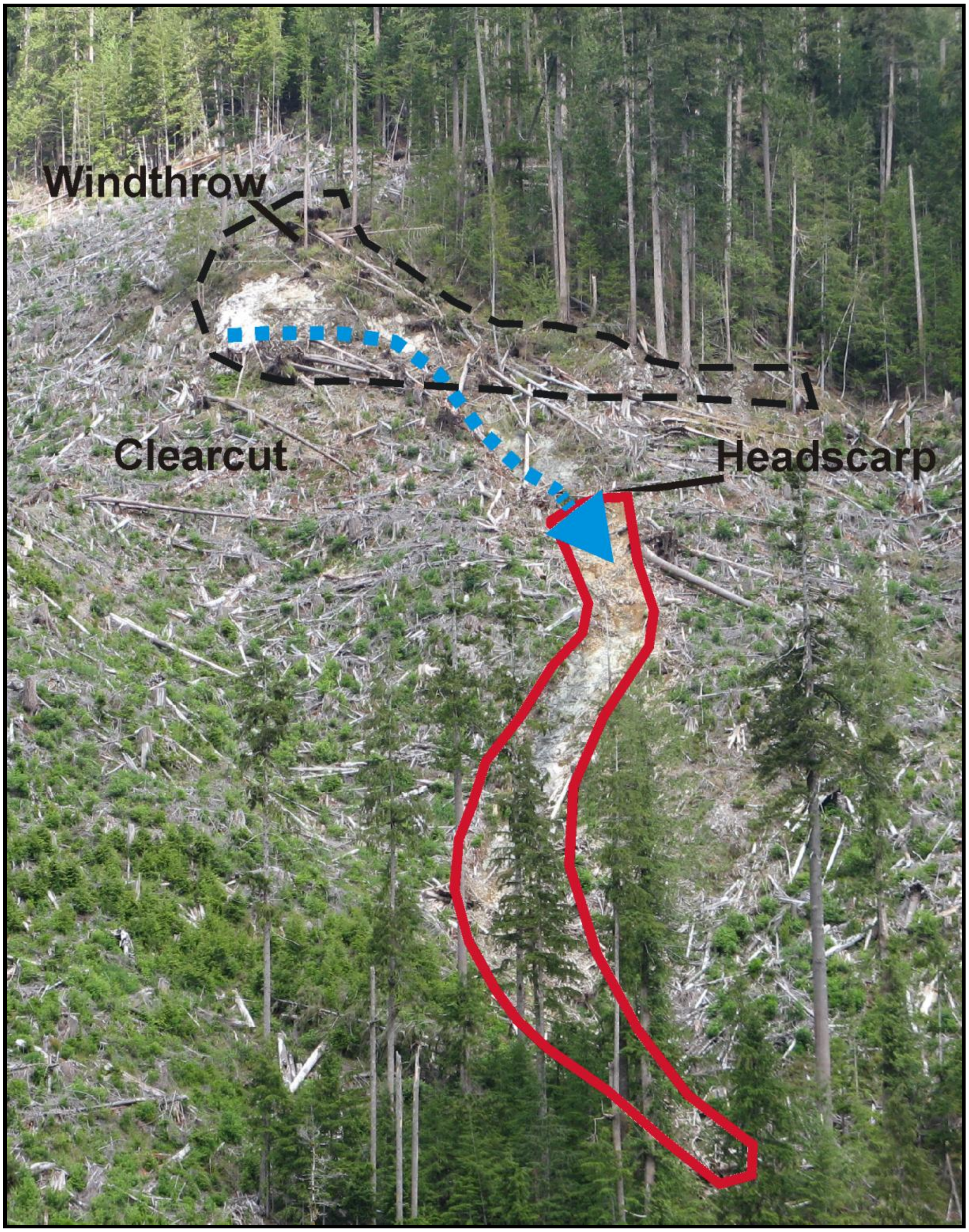



Figure 2.24: Windthrow disturbed drainage initiating clearcut landslide. The blue dashed line indicates disturbed surface flows from windthrow along the clearcut edge and downslope into the landslide initiation zone. There was evidence of ponding water behind root balls. Eroded forest floor and soil from concentrated surface flows was observed between root balls and above the landslide headscarp.

The overturning of trees during windthrow leads to a reduction in root reinforcement in three ways. These include loss of root cohesion, lateral root strength, and vertical anchoring root strength (Zhou et al., 1998; Schmidt et al., 2001; Dupuy et al., 2005).

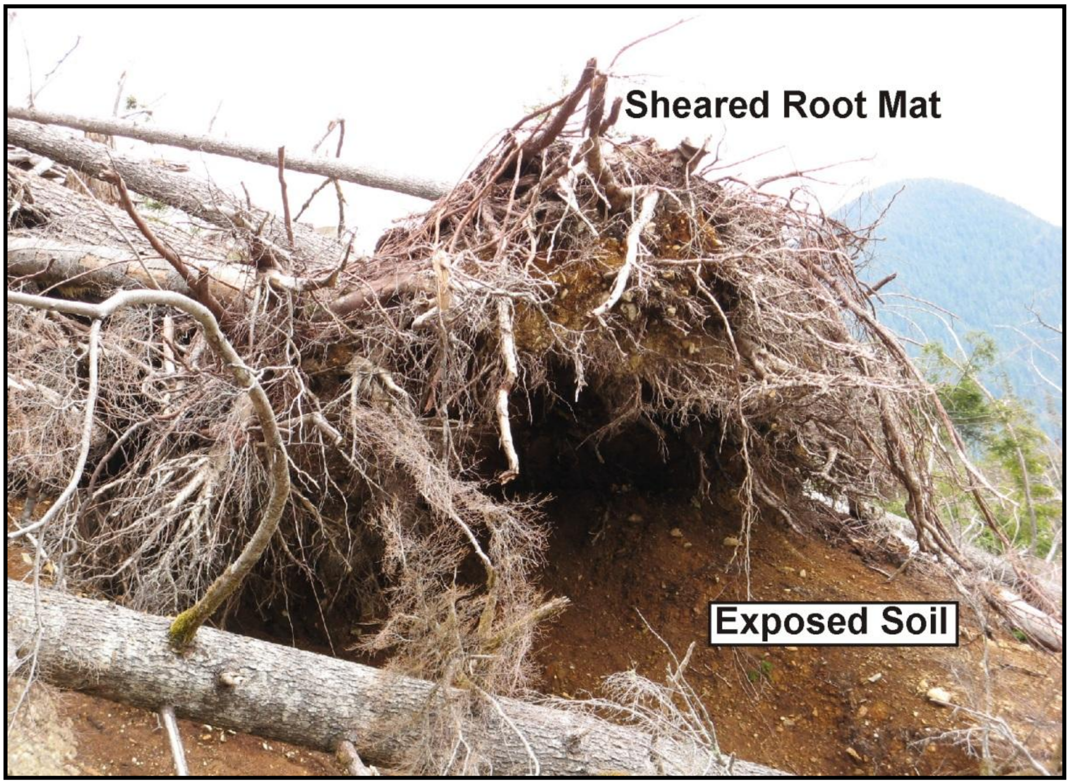



Figure 2.25: Sheared root mat at initiation zone of a windthrow landslide.

The lateral roots reinforce the upper 30 to 50 cm of the soil and when they break due to windthrow, the lateral root strength is reduced or lost (Figure 2.25). Lateral root strength is accomplished by soil arching or buttressing where the roots act as a reinforcing mat (O'Loughlin, 1974a; Nilaweera and Nutalya, 1999). Vertical root strength is enabled by root anchoring; roots can extend across the failure plane and wedge into the underlying soil or fractures in the bedrock, reinforcing the soil (Ekanayake and Phillipes, 1999; Pregitzer et al., 2002; Schwartz et al., 2010).

Windthrow results in the exposure of mineral soil and a loss of the forest canopy (Figure 2.26). A healthy intact forest canopy intercepts precipitation, delays precipitation inputs from high intensity cells in large storms, and helps reduce soil moisture through evapotranspiration; although evapotranspiration is probably a minor factor due to the size of the storm event and the time of year. The overturned, windthrown trees allow raindrops to reach the forest floor and directly impact and saturate the exposed mineral soil leading to slope instability (Iverson, 2000; Keim and Skaugset, 2003).

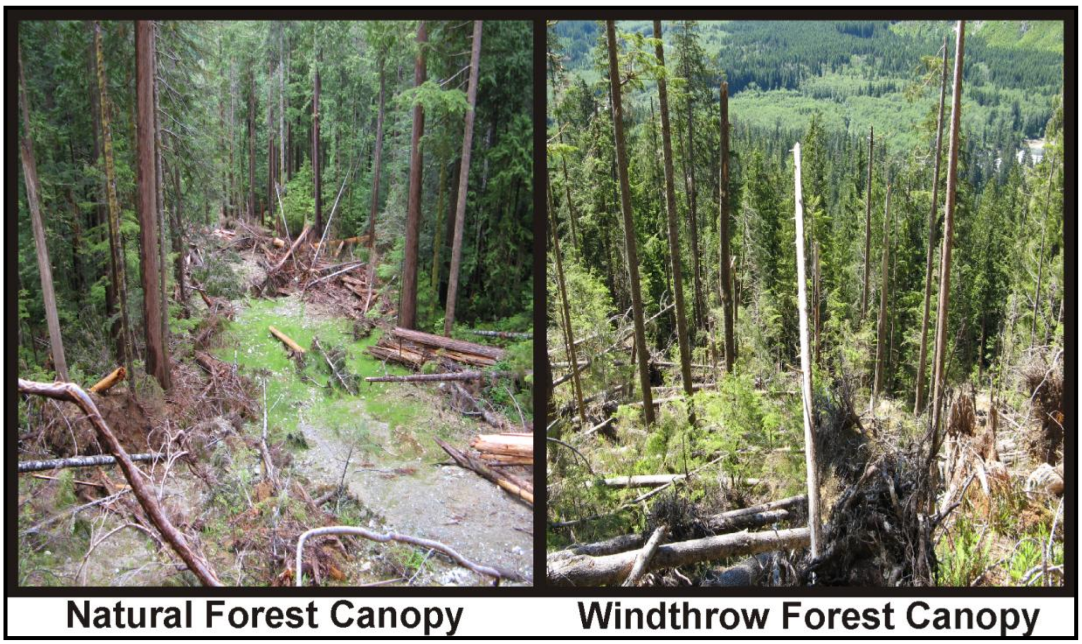



Figure 2.26: Forest canopy: An intact forest canopy adjacent to the runout zone of a landslide (left), a windthrow forest canopy near the initiation zone of a landslide. Note the reduced thickness of the forest canopy in the windthrown forest.

### 2.6.5 Comparison between Change Detection and Field/GIS Inventory

The inventory of landslides and windthrow with satteillite imagery identification combined with field reconnaisance was more reliable in determining the number and areal extent of landslides rather than solely using automated change detection. The SPOT 2004, 2006 and 2007 satellite imagery used for the change detection was 2.5 m or 5 m resolution whereas the imagery used to map the windthrow patches from WFP was 0.3 m resolution. The resolution of the imagery should be at least half the size of the object being observed (Pack, 2005). In other words, since we are observing stems of trees in windthrow, the resolution should be at least 0.5 m since most of the old growth trees observed had stem sizes between 0.5 and 1 m in diameter. The higher resolution orthophoto imagery, in conjunction with the field mapping and field truthing allowed identification of 104 additional landslides and better differentiation between windthrow and clearcuts.

The minimum and maximum landslide areas for the automated change detection and this field truthed study were 400 $m^2$ and 12470 $m^2$, respectively. However, four landslides in this study were less than 400 $m^2$ and only two landslides were less than 400 $m^2$ for the automated change detection. The mean landslide area for automated change detection and the field truthed data base were 11550 $m^2$ and 12470 $m^2$, respectively.

In addition, the field truthed data base identified 404 widnthrow patches compared to only 91 identified with the automated change detection. The minimum and maximum windthrow area for the automated change detection was 2865 $m^2$ and 128963 $m^2$, respectively.  The minimum and maximum windthrow area for the field truthed study was 752 $m^2$ and 640099 $m^2$, respectively.  The mean widnthrow area for automated change detection and this study was 31431 $m^2$ and 45156 $m^2$, respectively.

Based on the analysis of landslide and windthrow area it appears that the field truthed/high resolution imagery was better at detecting more landslides regardless of area. However it appears from this study that most of the landslides missed with change detection were in windthrow which is due to the poor resolution imagery not detecting landslides under the blown down trees.

Detailed analysis found that windthrow did have a major impact during this storm event in contrast to Guthrie et al. (2010) due to the large number of windthrow patches and landslides identified with high resolution imagery and field truthing. The integration of field reconnaissance mapping involving helicopters , vehicles and landslide event reports from licensees is necessary when completing a landslide/windthrow inventory rather than depending on a completely automated system.

## 2.7 Conclusions

The storm event on November 15, 2006 triggered numerous landslides by a combination of wind, wind driven rain, and wind and rain melting the existing snowpack. A subsequent landslide and windthrow inventory conducted on southwestern Vancouver Island provides new evidence on the importance of windthrow on landslide initiation. The density of windthrow related landslides is 25 times the clearcut density and 123 times the natural (non-windthrow) density. Windthrow landslides are primarily influenced by slope aspect, wind speed and direction, adjacent clearcut age and location, steep topography, and old growth timber. The influence of clearcut location on windthrow is not completely understood but could be related to cutblock edge proximity and maximum cutblock area or the location of adjacent inoperable terrain (Mitchell et al, 2001; Ruel et al., 2002). Although the distribution of landslides is highly variable over the project area, the identification of three main clusters of primarily windthrow landslides could also imply that intense storm cells impacted these areas leading to the large number of landslides.

A combination of satellite imagery and field reconnaissance is the most accurate method to use when conducting a windthrow landslide inventory. Automated change detection misidentified windthrow as clearcuts and failed to identify several landslides.

# 3: The Effects of Timber Harvesting on Root Reinforcement and Landslide Initiation, Southwestern Vancouver Island, British Columbia

## *3.1* Introduction

Forestry companies have engaged in logging on Vancouver Island for over a century, recently on steeper and less stable terrain. This terrain poses more hazards to resource users, fisheries, utilities, infrastructure, and recreation. Researchers such as Howes (1981, 1987), Rollerson et al. (1998 and 2002), Jakob (2000), and Millard et al. (2002) have published terrain attribute and landslide studies to describe the effects of logging on landslide activity. However, minimal research has focused on how logging affects root reinforcement on Vancouver Island.  Research on root reinforcement has been published for other regions and indicates a significant impact on slope stability (Burroughs and Thomas, 1977; Nilaweera and Nutalaya, 1999; Schwartz et al., 2010). O'Loughlin (1974b) conducted research on root strength after timber harvesting near North Vancouver, BC. Sakals and Sidle (2004) developed a model of how root cohesion changes after harvesting at two research forests on coastal British Columbia.

Research on a link between landslides and root reinforcement has been conducted in other regions such as the US Pacific Northwest, Alaska, Japan, and New Zealand. Burroughs and Thomas (1977) investigated the strength and density of roots after logging in Oregon and Idaho and found an exponential decline in root density in the first 10 years after logging.  Schmidt et al. (2001) studied the impact on root reinforcement using root area ratio for different land uses such as clearcuts <11 years old, industrial forests and natural forests. They showed that clearcuts and industrial forests have a lower root density than old growth forests even a century after timber harvesting. An increase in landslide rates between 2 and 10 years after logging and a 50% to 90% decline in root strength have led to conclusions (O'Loughlin and Ziemer, 1982; Burroughs and Thomas, 1977) that increased landslide rates are also related to root decay.

This research project commenced during the summer of 2007 on southwestern Vancouver Island after several large storm events between fall 2006 and winter 2007 triggered over 230 landslides in the Klanawa, Sarita, and Nitinat River valleys (Figure 3.1). A storm occurring between November 12 and 17, 2006 (hereafter referred to as the November 15, 2006 storm) caused the majority of the landslides, and was accompanied by high winds in excess of 100 km/hr. and 24 hour rainfall exceeding 240 mm. Forty-eight open slope landslides were investigated in the field and of these 24 were associated with clearcuts or second growth and 24 were associated with windthrow. A satellite imagery analysis combined with GIS was also conducted and identified 233 landslides consisting of clearcut, windthrow, natural and road-associated landslides.

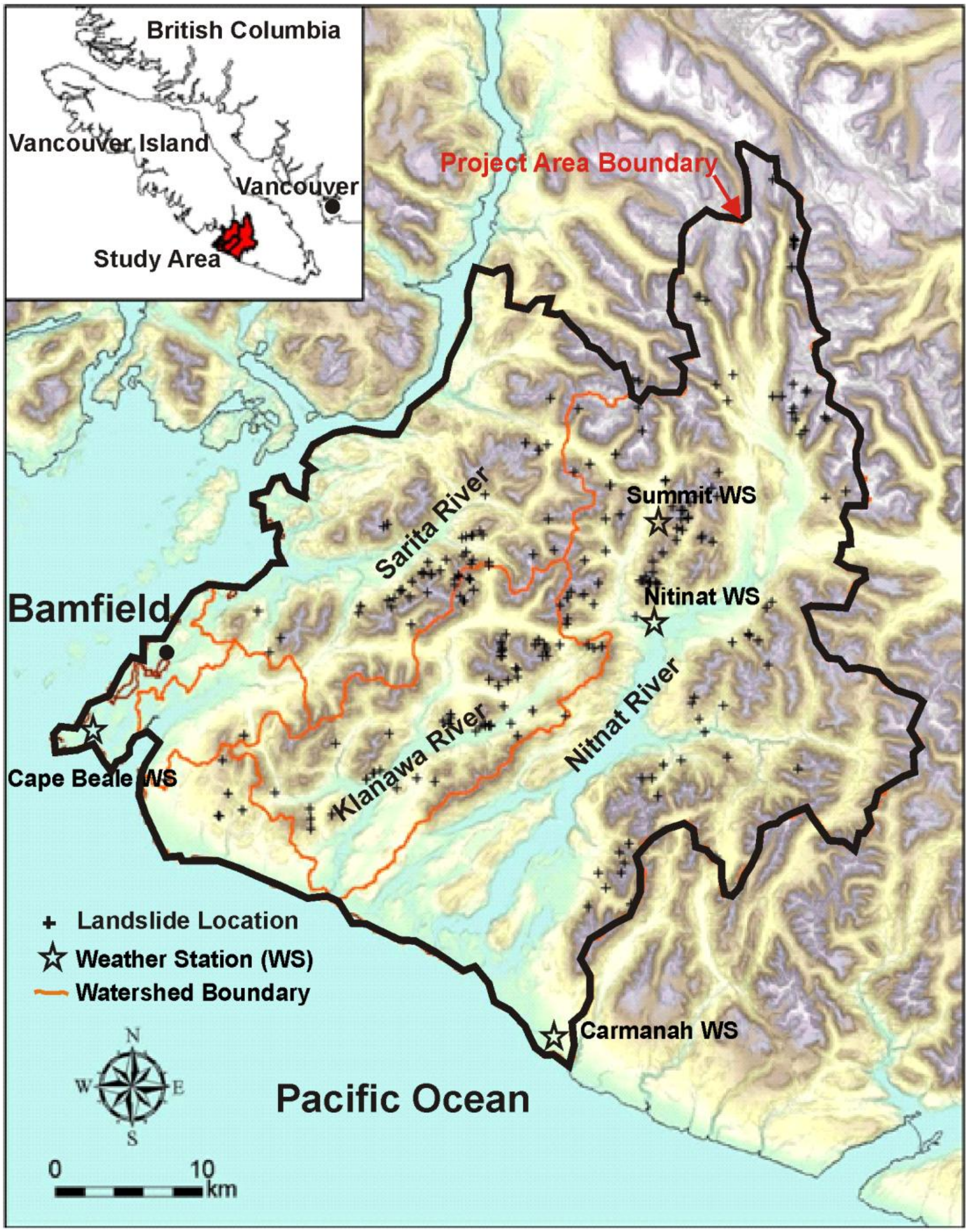



Figure 3.1: Project area location map showing 233 landslides analysed with satellite imagery and GIS. The 48 field truthed landslides are also located within this project area.

The four main objectives of this study are to:

1) research the effects of logging and forest health on root density and quality;

2) identify the period after harvesting that is most vulnerable to landslides due to root decay;

3) identify any rooting or forest stand characteristics that contribute to root density or root quality changes; and

4) compare the root density results from this study to other studies in the Pacific Northwest.

## *3.2* Setting

The research area is located on southwest Vancouver Island near the community of Bamfield, approximately 160 km west of Vancouver, BC. The project area is located in the Nitinat, Klanawa and Sarita River watersheds and is bounded to the west by Pacific Rim National Park and the Pacific Ocean, to the south and east by the Cowichan Lake watershed and Carmanah Provincial Park and to the north by Alberni Inlet. The majority of the area lies within Western Forest Products (WFP) and Teal Cedar Products tree farm licences (TFL), which include TFL 44 and 46, respectively, as well as other crown land licences such as Forest Licences and BC Timber Sales. Small parcels of private land also exist, primarily at low elevations, in the Sarita and Nitinat River valleys.

The climate is characterized by a wet and humid climate with cool summers and mild winters and low amounts of snowfall (Green and Klinka, 1994). Major rainfall events from moist Pacific air masses occur between October and March, and are associated with significant landslide activity. The study area contains two variants of the Coastal

Western Hemlock (CWH) Biogeoclimatic Zone: 1) the submontane very wet maritime variant (CWHvm1) between sea level and 600 m elevation and 2) the montane very wet maritime variant (CWHvm2) between elevations of 600 m and 1000 m (Green and Klinka, 1994). The CWH forests are dominated by tree species such as western hemlock (*Tsuga heterophylla)*, amabilis fir or balsam (*Abies amabilis)*, western redcedar (*Thuja plicata)*, and lesser amounts of Douglas-fir (*Pseudotsuga menziesii),* and Sitka spruce (*Picea sitchensis).*

The annual precipitation for the Nitinat River Hatchery weather station is 4000 mm with just over 2800 mm of precipitation between October and March (Figure 3.2). There was over 3900 mm of precipitation between October 2006 and March 2007, 40% greater than the mean precipitation for the same time period (Environment Canada, 2009b). One storm event between November 12 and 17 was associated with most of the landslides and had a total rainfall of 380 mm with a daily maximum of 240 mm at the Summit Forest Service weather station. This storm was associated with approximately a 1 in 15 year return period (Miles et al., 2008). Weather patterns such as rain on snow, wind driven rain, and wet antecedent conditions from previous storms were a factor in the initiation of most of the slope failures (Miles et al., 2008; Guthrie et al., 2010).

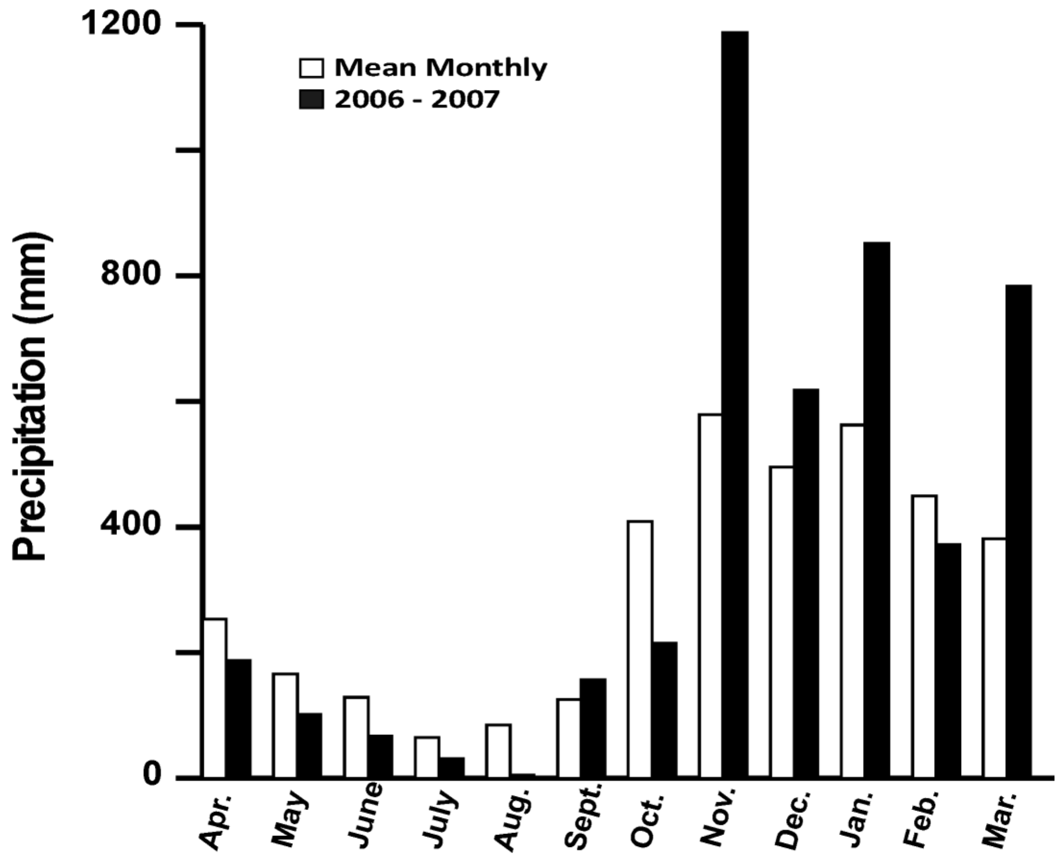



Figure 3.2: Nitinat River Hatchery weather station precipitation (Mean Monthly and 2006/2007) Environment Canada climate normals and averages 1971-2000 (Environment Canada, 2009b).

The Vancouver Island Ranges are the dominant mountain range on Vancouver Island and trend northwest - southeast through the study area. Pleistocene glaciations have developed U shaped valleys and fiords throughout the area and left thick till and glaciofluvial deposits on lower to middle slopes. Colluvium dominates the upper valley slopes and fluvial deposits occupy the valley bottoms (Holland, 1964).

A majority of the bedrock geology is Jurassic in age and consists of granitic intrusive rocks from the Island Plutonic Suite, West Coast Crystalline Complex and volcanic rocks from the Bonanza Group. Lesser amounts of Upper Eocene and Triassic age sedimentary rocks from the Vancouver and Carmanah Groups also exist in the area (Massey et al., 2005).

## 3.3 Methods

### 3.3.1 Sample Design and Data Collection

Landslides were selected based on three main criteria. First, the landslides had to be open slope landslides which were subdivided into clearcuts (≤15 years old), second growth (>15 years old) and unlogged forest. Second, the slope failures had to be new landslides from between November 2006 and March 2007 to allow the sampling of fresh exposed roots. Third, to reduce variability from climate, geology and vegetation, landslides were only selected from the Sarita, Klanawa, and Nitinat watersheds. The landslides were located using landslide event reports from WFP.

A total of 48 landslides were examined in the field including one clearcut and six windthrow-associated that were unsafe for root data collection (Figure 3.3). Consequently, root density data was only collected for 15 clearcut, eight second growth and 18 windthrow-associated landslides. The immediate area above the landslides was examined to ensure there was no road drainage influence above the landslide initiation zone. Terrain attributes such as slope gradient, soil depth and type, slope curvature and position, aspect, drainage, landslide dimensions and elevation were recorded on a British Columbia Forest Service Landslide Data Card (Figure 3.4). Root density, root quality and additional forest and terrain attributes were also recorded. The overall forest type was noted for each landslide but individual roots were not differentiated according to tree species.

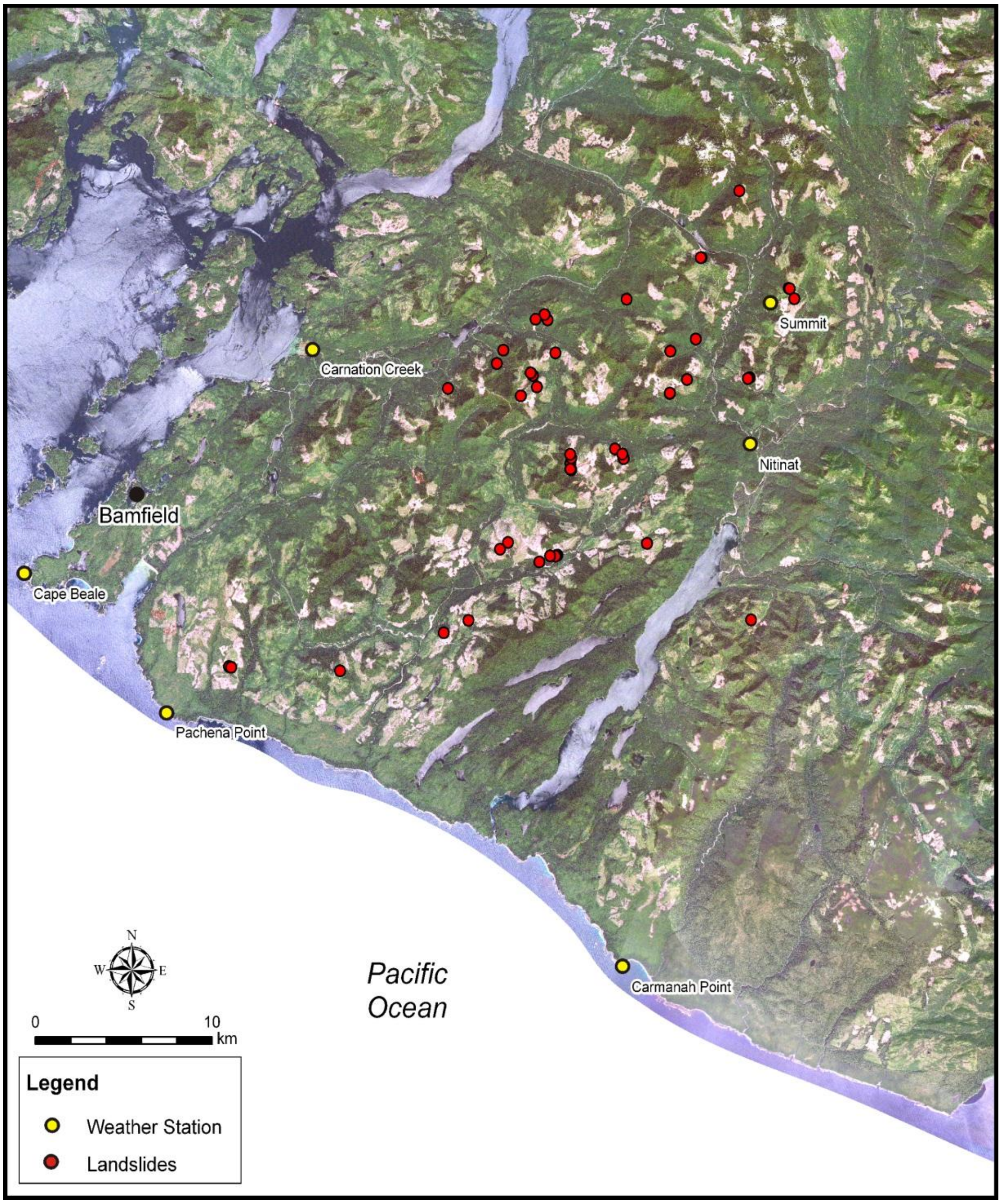
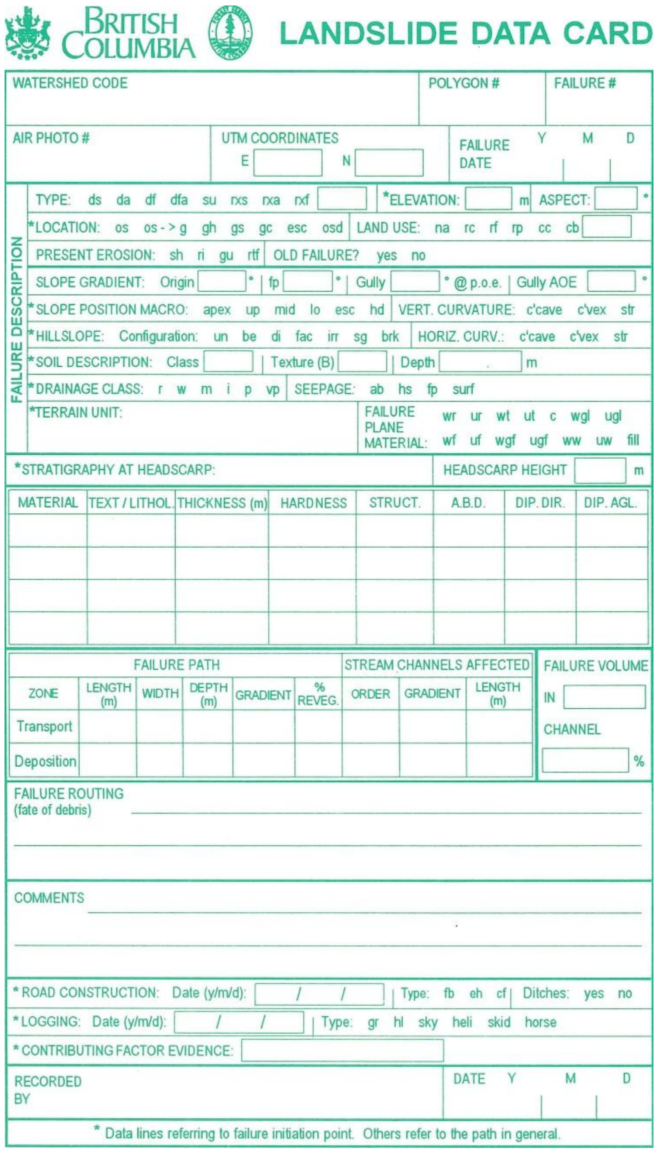



Figure 3.3: Site location map showing locations of 48 field investigated landslides.



BRITISH COLUMBIA

LANDSLIDE DATA CARD

WATERSHED CODE | POLYGON # | FAILURE #

AIR PHOTO # | UTM COORDINATES E N | FAILURE DATE Y M D

FAILURE DESCRIPTION

TYPE: ds da df dfa su rxs rxa rxf | *ELEVATION: m | ASPECT: °

*LOCATION: os os - > g gh gs gc esc osd | LAND USE: na rc rf rp cc cb

PRESENT EROSION: sh ri gu rtf | OLD FAILURE? yes no

SLOPE GRADIENT: Origin ° | fp ° | Gully ° @ p.o.e. | Gully AOE °

*SLOPE POSITION MACRO: apex up mid lo esc hd | VERT. CURVATURE: c'cave c'vex str

*HILLSLOPE: Configuration: un be di fac irr sg brk | HORIZ. CURV.: c'cave c'vex str

*SOIL DESCRIPTION: Class | Texture (B) | Depth m

*DRAINAGE CLASS: r w m i p vp | SEEPAGE: ab hs fp surf

*TERRAIN UNIT: | FAILURE PLANE MATERIAL: wr ur wt ut c wgl ugl wf uf wgf ugf ww uw fill

*STRATIGRAPHY AT HEADSCARP: | HEADSCARP HEIGHT m

| MATERIAL | TEXT / LITHOL. | THICKNESS (m) | HARDNESS | STRUCT. | A.B.D. | DIP. DIR. | DIP. AGL. |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

| FAILURE PATH | | | | | | STREAM CHANNELS AFFECTED | | |
|---|---|---|---|---|---|---|---|---|
| ZONE | LENGTH (m) | WIDTH | DEPTH (m) | GRADIENT | % REVEG. | ORDER | GRADIENT | LENGTH (m) |
| Transport | | | | | | | | |
| Deposition | | | | | | | | |

FAILURE VOLUME: IN | CHANNEL %

FAILURE ROUTING (fate of debris)

COMMENTS

* ROAD CONSTRUCTION: Date (y/m/d): / / | Type: fb eh cf | Ditches: yes no

* LOGGING: Date (y/m/d): / / | Type: gr hl sky heli skid horse

* CONTRIBUTING FACTOR EVIDENCE:

RECORDED BY | DATE Y M D

* Data lines referring to failure initiation point. Others refer to the path in general.

Figure 3.4: BC Forest Service Landslide Data Card used for field data collection (MOFR, 2009).

Satellite SPOT 2007 imagery and GIS shape files (Caslys Consulting, 2007) were obtained from the British Columbia Ministry of Environment and used to locate additional clearcut landslides and calculate a clearcut landslide density. Six additional open slope and twenty-nine gully clearcut landslides were identified with the SPOT 2007 satellite imagery. These additional landslides were not field checked but were combined with the field data set to increase the sample size and calculate the landslide density. From these additional clearcut landslides we can draw some conclusions as to whether the landslide density was influenced by root decay.

Significant differences were observed between some windthrow and clearcut related landslides. The terrain and soil conditions characterizing windthrow sites were thin, dry, soils with steeper slopes compared to thicker, wetter soils with gentler slopes for clearcuts. In order to compare the windthrow and clearcut sites on the same basis, only five windthrow landslides were selected to represent old growth forest roots prior to logging. These five sites were similar to clearcuts with thicker soils, gentler slopes and better growing locations than most of the other windthrow areas. Trees in the old growth windthrow sites were characterized by root rot, broken tops, and other forest health issues. The age of the windthrow polygons were identified from digital forest cover information. The remaining 13 windthrow associated landslides were excluded from the root density analysis.

A root density sampling procedure was developed to assess the rate of root decay after timber harvesting. Three to four root density plots were sampled at each landslide headscarp at random locations with the top of the plot cross section being at the base of the ‘A’ soil horizon. A majority of sample plot dimensions were 40 cm by 40 cm; narrower rectangular plots with the same cross sectional area were used for thinner soils. The sample plot dimensions were based on the general rooting depth observed at the landslide headscarps. This contrasts previous root reinforcement studies that have used hand dug pit dimensions of 1 m deep and 1 m wide (Schmidt et al. 2001; Burroughs and Thomas, 1977). In this study, the roots were measured by the same person to maintain consistency and were completed between seven and nine months after the slope failures occurred. Root diameter was measured for all roots, regardless of tree species, and tallied into five diameter classes (Table 3.1). The first two diameter classes were based on research by Burroughs and Thomas (1977). In addition, root diameters >15 mm were measured to the nearest 5 mm. Roots <1 mm diameter were not tallied (Schmidt et al. 2001) since they were too small to distinguish from shrub and herbaceous roots. However, some research has shown that these fine roots are important for slope stability (Pollen, 2007).

Table 3.1: Root diameter classes.

| **Diameter Class** | **Class 1** | **Class 2** | **Class 3** | **Class 4** | **Class 5** | **Not Recorded** |
|---|---|---|---|---|---|---|
| Root Diameter (mm) | 1 – 5 mm | >5 – 10 mm | >10 – 15 mm | > 15 mm<br>Recorded to nearest 5 mm | All diameters combined | < 1 mm |

A root quality designation was assigned to each diameter class for each sample plot, and then for each root diameter class the three to four sample plots were averaged for the entire landslide. However, post landslide root condition may not be indicative of pre-landslide root condition due to mechanical damage during the slope failure. In addition, groundwater and soil drainage conditions could affect the quality of roots and levels of decay. Roots were given three quality designations (Table 3.2). No root quality designations are known to exist in the literature reviewed. Burroughs and Thomas (1977) noted obvious decay and resinous roots in their root strength research.

Table 3.2: Root quality designations

| **Root Quality** | **Bark Condition** | **Flexibility** | **Deterioration** |
|---|---|---|---|
| Good | Tight bark | Flexible | None |
| Moderate | Loose bark | Low flexibility | Minor deterioration |
| Poor | Little to no bark | Breaks easily | Little woody material, advanced decay |

Absent roots in a diameter class were left blank in the notes so they would be distinguished separately from the poor quality roots. If a root diameter was absent there could be two reasons, either the roots were never present in that diameter class or the roots of that diameter have decayed.

Other root characteristics such as rooting failure, shape, depth, and lateral or vertical rooting were noted for each sample plot. Rooting failure was visually estimated by comparing the number of roots failing by breakage to the number failing by slippage. A general percent breakage was noted for all diameter classes combined at each sample plot and then an overall average was calculated for the entire landslide. Root shape was measured, similar to root breakage, by comparing the number of roots that were straight to the number of crooked roots.

### 3.3.2 Data Analysis

For each root diameter class, the number of roots/m$^2$ and the root area ratio (RAR) were calculated. The number of roots/m$^2$ was calculated by summing the total number of roots (n) in each diameter class and dividing the sum of the roots by the total cross sectional area of soil (As) in the sample plots. The RAR was determined by the following equation:

Equation 1: RAR = $_{(i=1)}\Sigma\, n_i{*}Ar_i/As = (n\prod d_r)/(L * W)$

where Ar is the cross sectional area of the roots, n is the total number of roots, L and W are the dimensions of the sample plot in metres, and $d_r$ is the average root diameter.

A WFP harvest year overview map and digital forest cover map were used to identify the harvest age for each clearcut where a landslide was present. The harvest ages were plotted against the root density measurements for each diameter class to determine any linear or exponential relationships due to changes in root density.

Univariate statistical analyses were conducted to test the rates of decay or growth of roots over time as well as changes in root density with an increase in soil depth. Due to the small sample size, some of the data were not from a normal distribution and therefore, the raw data were used to better illustrate the trends. A p-value of $P \leq 0.05$ was considered significant and therefore evidence to reject the null hypothesis. The adjusted $R^2$ values are indicated in the figures to illustrate the amount of scatter in the data.

## 3.4 Results

### 3.4.1 Landslide Harvest Age Distribution

The harvest age distribution was examined for 30 open slope and 29 gully, clearcut and second growth associated landslides, which included 24 field truthed open slope landslides, and 35 landslides (6 open slope and 29 gully) identified from satellite imagery (Figure 3.5). Forty percent of open slope landslides occurred within clearcuts that were between 3 and 15 years old and 27% occurred within clearcuts that were ≤ 2 years old. The high density of landslides within the first two years after logging is similar to other studies such as Burroughs and Thomas (1977) on the Oregon Coast and Horel (2006) on northern Vancouver Island. The large number of landslides could be due to changes in hydrology (Keim and Skaugset, 2003), destruction of macropores during logging (Ziemer, 1992; Uchida; 2004), disturbed surface water drainage patterns due to windthrow or yarding corridors, or the rapid decay of roots (Ammann et al., 2009). Two thirds of the 30 open slope landslides occurred within the first 11 years after harvesting. Second growth stands between 18 and 63 years old (a 45 year period) accounted for the remaining third of the open slope landslides. The landslide density is significantly higher in the first 11 years after harvesting than in any other harvest age period. The higher density in the first 15 years after harvesting was illustrated in Chapter 2. The landslide density was 0.25 landslides/$km^2$ for clearcuts ≤15 years compared to 0.09 landslides/$km^2$ for clearcuts >15 years old. The difference in landslide density was probably a result of a majority of the slopes within older clearcuts already failing, whereas sensitive slopes in younger clearcuts are still occurring and resulting in more slope failures. Another contribution to the higher landslide density is that the younger clearcuts are continuing to experience root decay in comparison to the older clearcuts which are experiencing root renewal from plantation re-growth. The contrast between root decay and root re-growth for the two clearcut age classes is resulting in the difference between landslide densities.

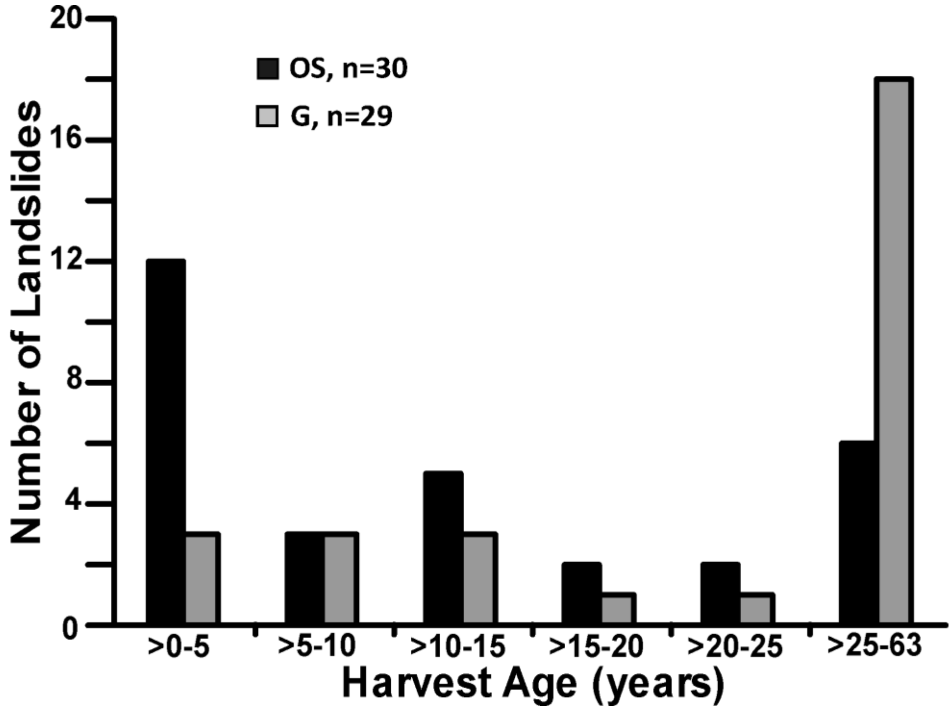



Figure 3.5: Number of landslides for each 5 year harvest age period from satellite imagery and GIS analysis. OS = open slope and G = gully (n=59)

The age distribution of clearcut landslides for the entire project area was analysed for both open slope and gullied terrain (Figure 3.5). The age distribution of landslides between open slope and gullied terrain was not proportional. Forty percent of open slope clearcut landslides occur in clearcuts ≤ 5 years old whereas only 10% of landslides in gullied terrain occur in the ≤ 5 year old age class.

On gullied terrain, 3 times as many landslides occur in clearcuts >25 years old compared to open slope terrain (Figure 3.5). Sixty-two percent of the landslides occur in gullied terrain for clearcuts >25 years old. This difference is attributed to harvesting practices that were conducive to landslide generation such as logging steep gullies. The implementation of the Forest Practices Code in 1995 has contributed to a reduction in the number of gullied terrain polygons that were logged resulting in fewer landslides. Therefore, there are fewer gullied clearcuts <10 years old to fail.

A subset of 45 landslides within TFL 44, approximately 72% of the project area, was used to determine the landslide density on slopes greater than 20˚ to compare to previous studies. TFL 44 was used in the calculation of the landslide density since there was only complete forest cover information for this area within the project area. The clearcut (≤15 years old) landslide density was 0.25 landslides/km$^2$. The clearcut landslide density is higher than previous studies. Jakob (2000) reported 0.05 ls/km$^2$ to the north at Clayoquot Sound and Wolter et al. (2010) indicated 0.08 ls/km$^2$ near Vancouver, BC in the Chilliwack River Valley.

### 3.4.2 Root Density Measurements

Root density was analysed using two methods, roots per square metre (roots/m$^2$) and root area ratio (RAR). Roots/m$^2$ is simply a count of the number of roots within a defined headscarp sample area. This type of analysis was used in a study by Burroughs and Thomas (1977). Schmidt et al. (2001), Bischetti et al. (2005) and Abdi et al. (2009) used RAR analysis to determine the root density within the headscarp of landslides.

We visually analysed the data and determined that diameter classes 1 and 2 as well as diameter class 5 for the number of roots/m$^2$ had a specific root density minimum at about 11 years after logging (Figure 3.6 a, b, e). Therefore, we used 11 years to divide the data for the bivariate fit analysis. The other root diameter classes (Figure 3.6 c, d) did not show an obvious trend before and after 11 years or at any other age. Consequently, the bivariate fit analysis was completed using a linear fit between 0 and 51 years for the remaining diameter classes.

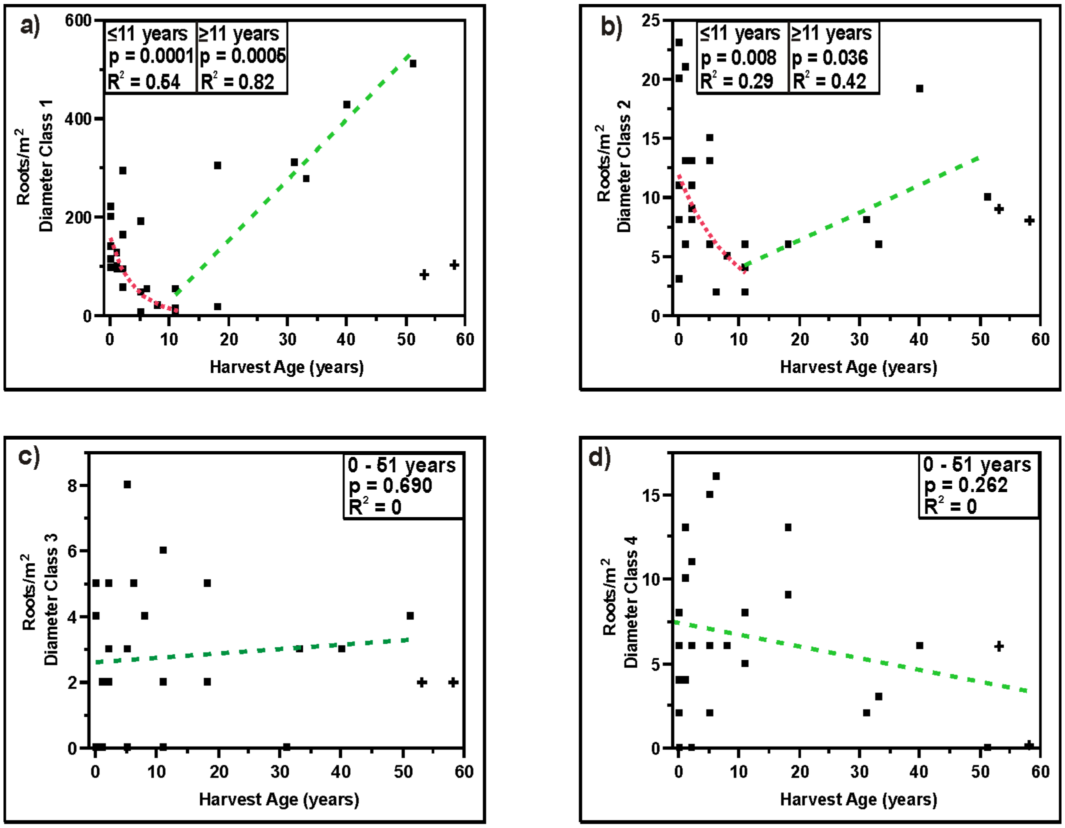
There is a change in root density with respect to time after timber harvesting (Figure 3.6). An exponential decrease was observed in the number of roots/m$^2$ within the first 11 years after harvesting and then a linear increase in root density between 11 and

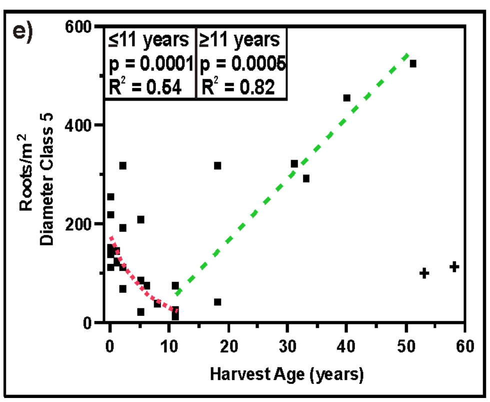
51 years. Root diameter classes 1 and 2 (Figure 3.6 a, b and e) showed a root density low at approximately 11 years after logging. There was no significant change in root density for classes 3 and 4 (Figure 3.6 c and d) between 0 and 51 years after logging. The two landslides with the oldest harvest ages (53 and 58 years) were omitted from the analysis and are shown in the figures as “+” signs. These outliers are likely due to shallow, rocky soils reducing the amount of soil available within each sample plot for root growth. These outliers have very low root densities in classes 1 and 2 when compared to other landslides with harvest ages between 31and 51 years.

Between the ages of 0 and 11 years the exponential decrease in the number of roots/$m^2$ within diameter classes 1, 2, and 5 are significant at the 0.01 level (Figure 3.6 a, b and e). Diameter class 1 represents approximately 95% of the total root density. Thus, the trend observed in diameter class 5, (Figure 3.6 e) is controlled by diameter class 1.

The linear increase in root density between the ages of 11 and 51 years within classes 1 and 5 are significant at the <0.0001 level (Figure 3.6 a and e). The linear increase in the class 2 roots is also significant at the 0.05 level (Figure 3.6 b).

A transformed natural logarithm (log) fit was used to analyse the exponential rate of decay with in the first 11 years after logging (Figure 3.7 a, b) and a linear fit was used to show the predominantly linear growth after 11 years (Figure 3.6 a, b). Diameter classes 1 and 2 showed the most significant decrease in the number of roots/$m^2$. The amount of decay at the root density low, 11 years after harvest, when compared to the windthrow forest at zero years is 93% and 69% for root classes 1 and 2, respectively (Table 3.3).




| Root Diameter (mm) | Diameter Class |
|---|---|
| 1 to 5 | 1 |
| >5 to 10 | 2 |
| >10 to 15 | 3 |
| >15 | 4 |
| All Root Diameters | 5 |

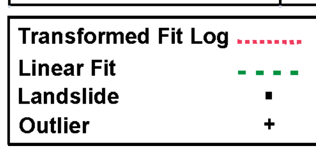



Figure 3.6: Root density regression curves for number of roots/m$^2$ versus harvest age by Diameter Class: a) Diameter Class 1, b) Diameter Class 2, c) Diameter Class 3, d) Diameter Class 4 and e) Diameter Class 5 (n = 28).

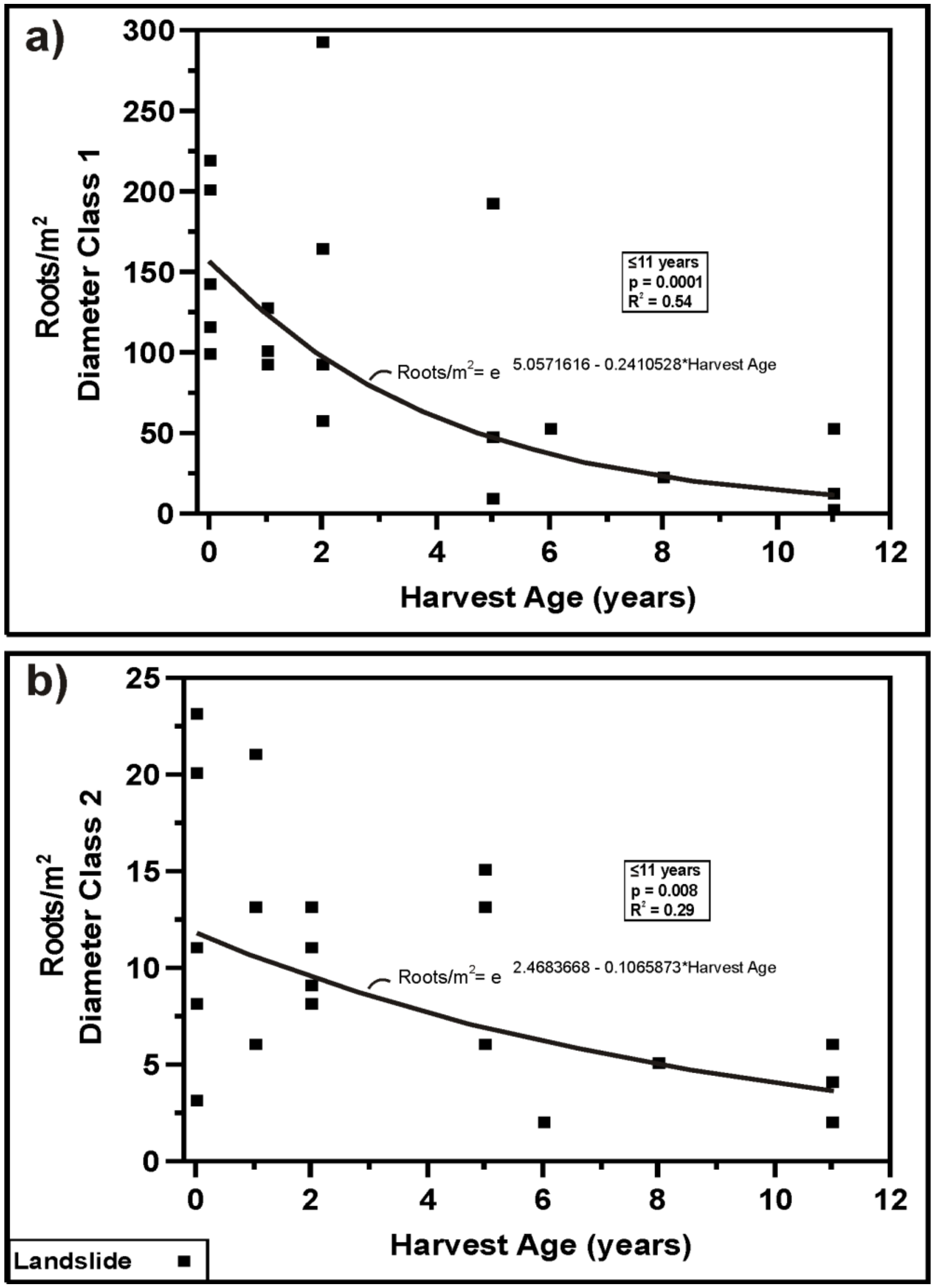



Figure 3.7: Exponential decay of roots in the first 11 years after logging for diameter classes 1 and 2: a) 1 to 5 mm diameter (Class 1) and b) >5 to 10 mm (Class 2).

The results of the log fit for class 1 are similar to research conducted by Burroughs and Thomas (1977). Approximately 50% of the original root density is lost within three to seven years after logging for classes 1 and 2 respectively. Similarly, O'Loughlin (1974a); Wu and Sidle (1995); and Sidle and Ochiai (2006) also found that 50% of the original root strength was lost within 3 to 5 years after timber harvesting. The current project confirms that root density on southwestern Vancouver Island follows a similar trend to previous research in other areas of the Pacific Nortthwest with a loss of up to 50% root density in the first three to seven years.

Growth for the two smallest diameter classes is linear between 11 and 51 years after harvesting. The time to recover to a similar root density as the original old growth windthrow forest is 21 years and 44 years for diameter classes 1 and 2, respectively. The total root density in second growth forest landslide sites, 51 years after harvesting, is 240% and 15% greater than the windthrow landslide sites, in the old growth forests, for diameter classes 1 and 2, respectively. Assuming that the windthrow areas are representative of old growth forest, this may indicate that second growth forests can recover to higher root densities than the original old growth forests. However, windthrow sites were selected based on the presence of landslides, so root density may be anomalously low. Since the one and two year old clearcuts have similar root densities to the windthrow, it is likely that the windthrow landslides are a good representation of the original old growth root density.  Another reason for the high root densities in the second growth stands is due to the species growing within these forests.  The second growth stands were predominantly forested with Douglas-fir, which have more dense root systems and less decay than old growth forests with mainly western hemlock and redcedar trees.

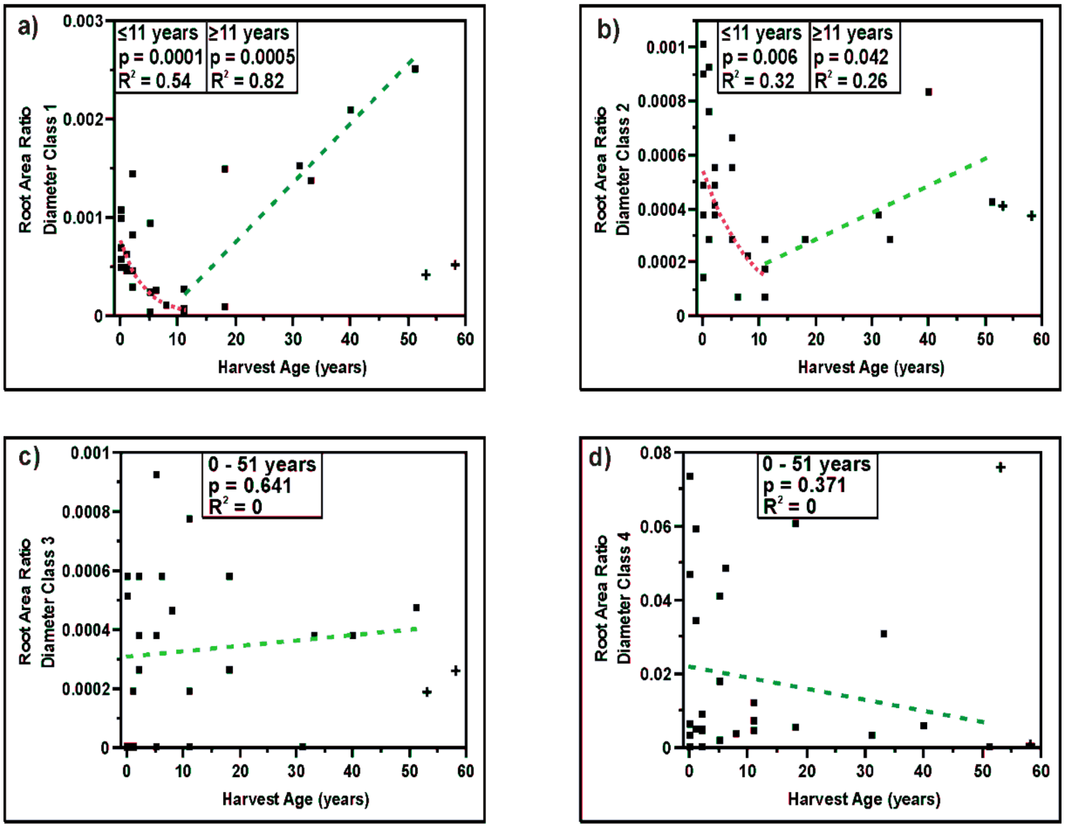
Table 3.3: Average rates of decay and growth for the two smallest root diameter classes. Decay = D (-); Root density is less than harvest age 0, Growth = G (+); Root density is greater than harvest age 0.

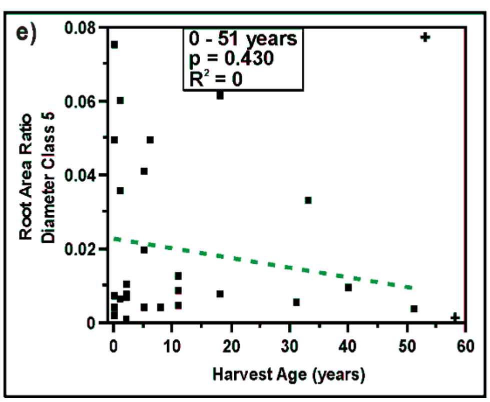
| Harvest Age (years) | # Roots/m$^2$ Class 1 | D or G % | # Roots/m$^2$ Class 2 | D or G % |
|---|---|---|---|---|
| 0 | 157 | 0 | 12 | 0 |
| 1 | 123 | -21 | 11 | -10 |
| 2 | 97 | -38 | 10 | -19 |
| 3 | 76 | -51 | 9 | -27 |
| 4 | 60 | -62 | 8 | -35 |
| 5 | 47 | -70 | 7 | -41 |
| 6 | 37 | -76 | 6 | -47 |
| 7 | 29 | -81 | 6 | -53 |
| 8 | 23 | -85 | 5 | -57 |
| 9 | 18 | -89 | 5 | -62 |
| 10 | 14 | -91 | 4 | -66 |
| 11 | 11 | -93 | 4 | -69 |
| 18 | 127 | -19 | 6 | -51 |
| 31 | 287 | +83 | 9 | -25 |
| 40 | 398 | +153 | 11 | -7 |
| 51 | 534 | +240 | 14 | +15 |

The results for RAR were similar to that of the roots/m$^2$ for the two smallest diameter classes (Figure 3.8). An exponential decrease was observed in the RAR within the first 11 years after harvesting and a linear increase in root density between 11 and 51 years. Root diameter classes 1 and 2 (Figure 3.8 a and b) show a root density low at approximately 11 years after logging whereas classes 3, 4 and 5 (Figure 3.8 c, d and e) show no significant change. As with the previous analysis, the two oldest harvest aged landslides, 53 and 58 years, were omitted from the analysis since they were outliers, likely due to shallow, rocky soil conditions.

The decreases in RAR for classes 1 and 2 between the ages of 0 and 11 years are significant at the 0.01 level (Figure 3.8 a and b). Classes 1 and 2 represent less than 10% of the total root area therefore, the RAR is heavily weighted to the larger root diameter classes (>15 mm) which represent nearly 90% of the cross sectional root area. Diameter classes 3 and 4 show no significant decrease or increase in RAR between 0 and 51 years.

The linear increase in root density between the ages of 11 and 51 years for classes 1 and 2 are significant at the <0.001 and 0.05 level, respectively (Figure 3.8 a and b). No significant trend was observed in the other diameter classes. The rates of decay and growth are comparable to that of the roots/$m^2$ for the two smallest diameter classes.




| Root Diameter (mm) | Diameter Class |
|---|---|
| 1 to 5 | 1 |
| >5 to 10 | 2 |
| >10 to 15 | 3 |
| >15 | 4 |
| All Root Diameters | 5 |


Figure 3.8: Root density regression curves for root area ratio (RAR) by Diameter Class: a) Diameter Class 1, b) Diameter Class 2, c) Diameter Class 3, d) Diameter Class 4 and e) Diameter Class 5 (n = 28).

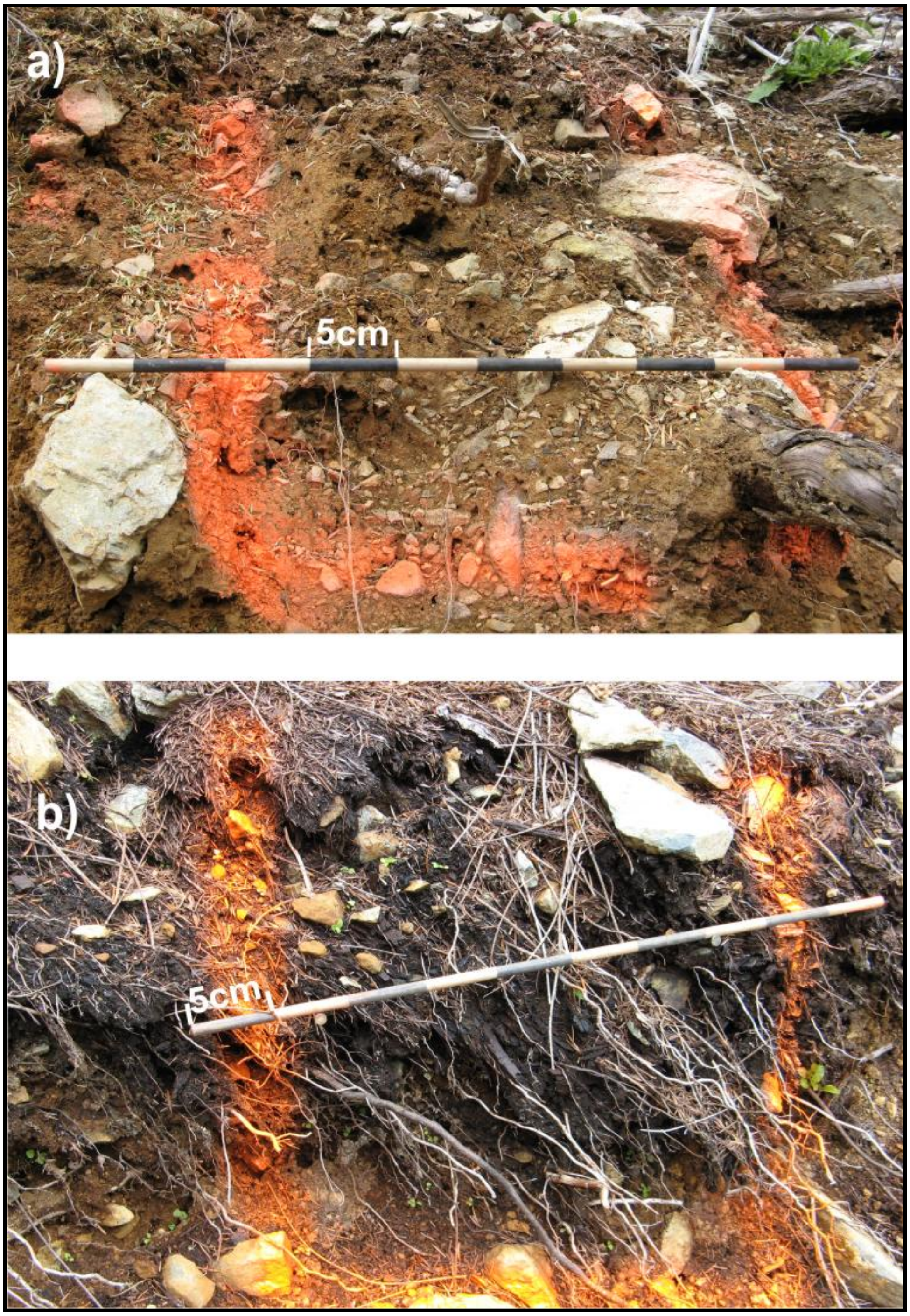



Figure 3.9: a) Low root density (25 roots/$m^2$) in a 5 year old clearcut, b) High root density (306 roots/$m^2$) in a 33 year old second growth stand. The orange painted lines outline the 0.4 m by 0.4 m sample plot. Note the roots are primarily growing in the top 0.4 m of the soil profile.

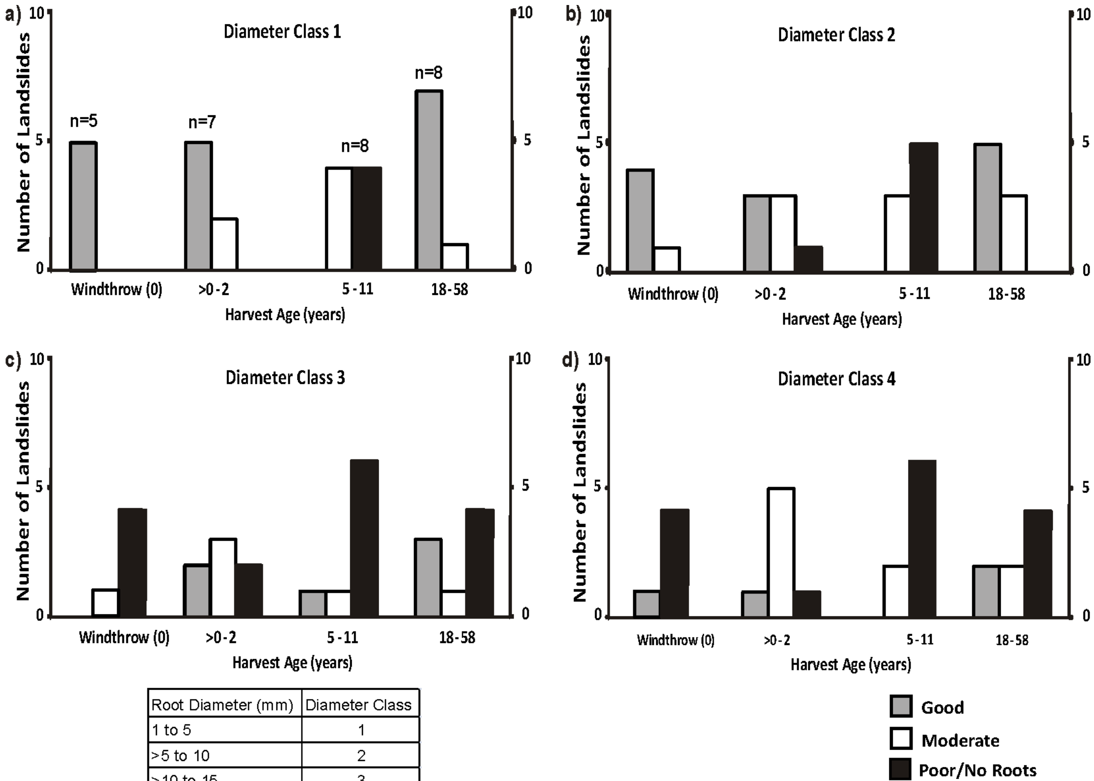
The various levels of root density were also observed during field data collection (Figure 3.9). Low root density was evident in a 5 year old clearcut which had very few roots <10 mm in diameter and only two larger diameter roots (Figure 3.9 a). The low number of roots in the smaller diameter classes indicates that these roots have probably decayed since harvesting and have not been replaced by the recently planted seedlings. In contrast, higher root density was present in a 31 year old second growth stand, with a large number of roots <10 mm in diameter (Figure 3.9 b). The small roots and a majority of large roots from the old growth forest decayed many years ago, however, the smaller roots have been replaced by trees planted over the past 30 years.

### 3.4.3 Root Quality

This qualitative assessment demonstrates that root quality varies with both the age and the stand land use. The root quality for each landslide and diameter class was plotted and displayed according to harvest age class (Figure 3.10 a, b, c and d). Windthrow sites were used as a baseline for a natural stand with no decay due to logging. Recent clearcuts ≤11 years old were divided into age classes, >0-2 years old and 5-11 years old. There were no landslides sampled for root density or quality in 3 and 4 year, and 12 to 17 year old clearcuts. Second growth stands, 18 to 58 years old comprised the final age group.

Diameter classes 1 and 2 show the most significant differences in root quality (Figure 3.10 a and b). There are no good quality roots in the 5-11 year old clearcuts for diameter classes 1 and 2. This poor root quality also coincides with the root density low point (Figure 3.6 a and b). A majority of good quality roots are present in the >0-2 year old clearcuts, windthrow, and second growth. Root decay is more prevalent in clearcuts between 5 and 11 years old (Figure 3.11 a) and most good quality roots are present in second growth stands (Figure 3.11 b). Moderate root quality was observed but was not prevalent for any particular age or diameter class (Figure 3.12).

Diameter classes 3 and 4 show no difference in root quality over time (Figure 3.10 c and d). The larger root diameters have very few good quality roots and are predominantly moderate or poor quality. The low number of good quality roots is due to larger roots being damaged by wind (Mitchell et al. 2001)) or root disease (Everham and Brokaw, 1996; Nowacki and Kramer, 1998). This may be particularly true for the windthrow roots, which are vulnerable to wind damage along the cutblock edges. The damaged roots can lead to poorer quality roots in those diameter classes. The smaller roots may not be damaged since they can repair the damage more rapidly than larger roots (Stokes et al., 2008). However, the large number of poor quality large roots and good quality small roots could be due to the tree species present at the landslide sites. The large roots could be lower quality western hemlock roots, whereas the small roots could be higher quality redcedar and Douglas-fir roots.




| Root Diameter (mm) | Diameter Class |
|---|---|
| 1 to 5 | 1 |
| >5 to 10 | 2 |
| >10 to 15 | 3 |
| >15 | 4 |

Figure 3.10: The number of landslides vs. Root Quality for each diameter and age class: a) Diameter Class 1, b) Diameter Class 2, c) Diameter Class 3 and d) Diameter Class 4. Note: No root data was collected for landslides in clearcuts ages 3 to 4 years old and 12 to 17 years old because there were no landslides in these age ranges. (n=28)

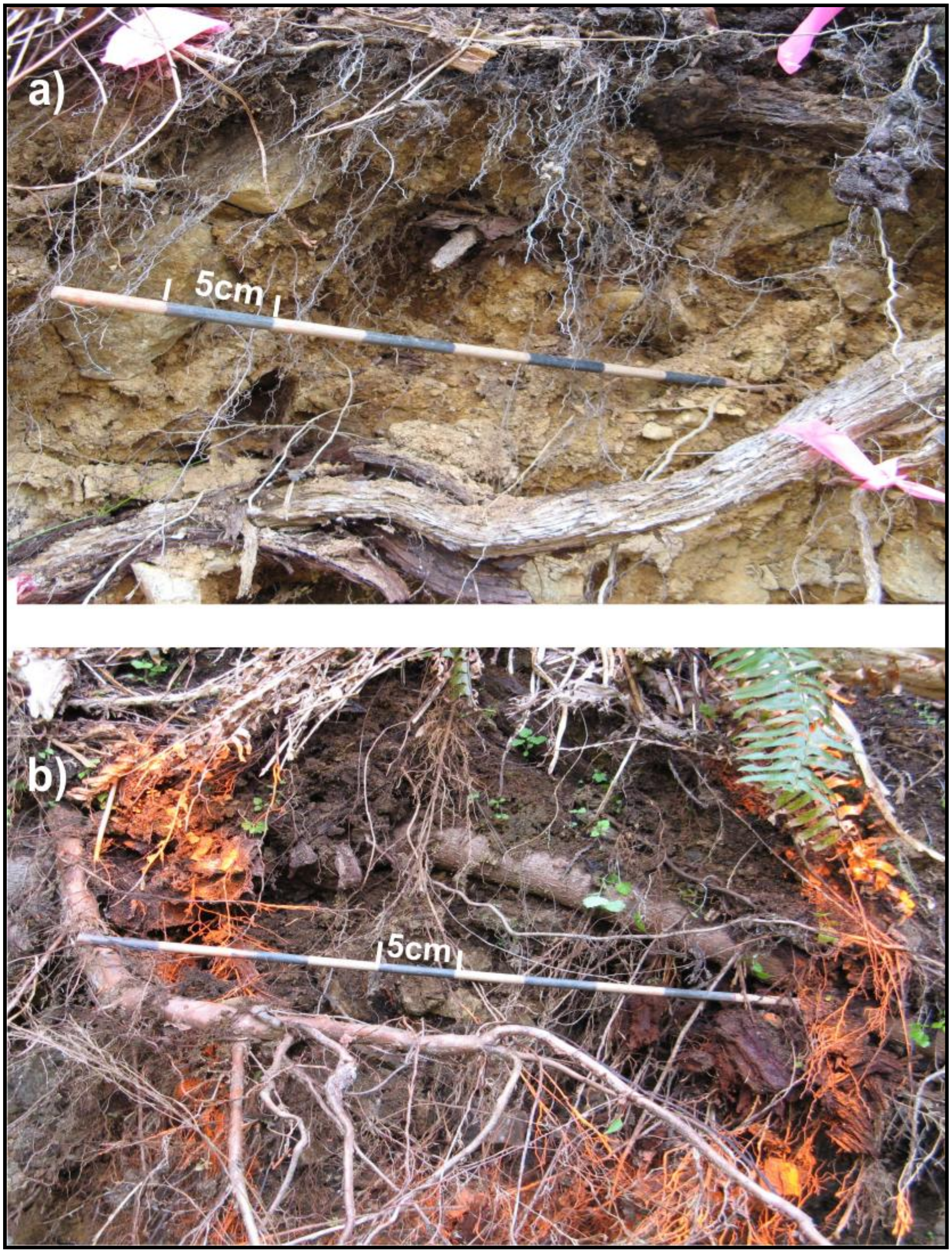
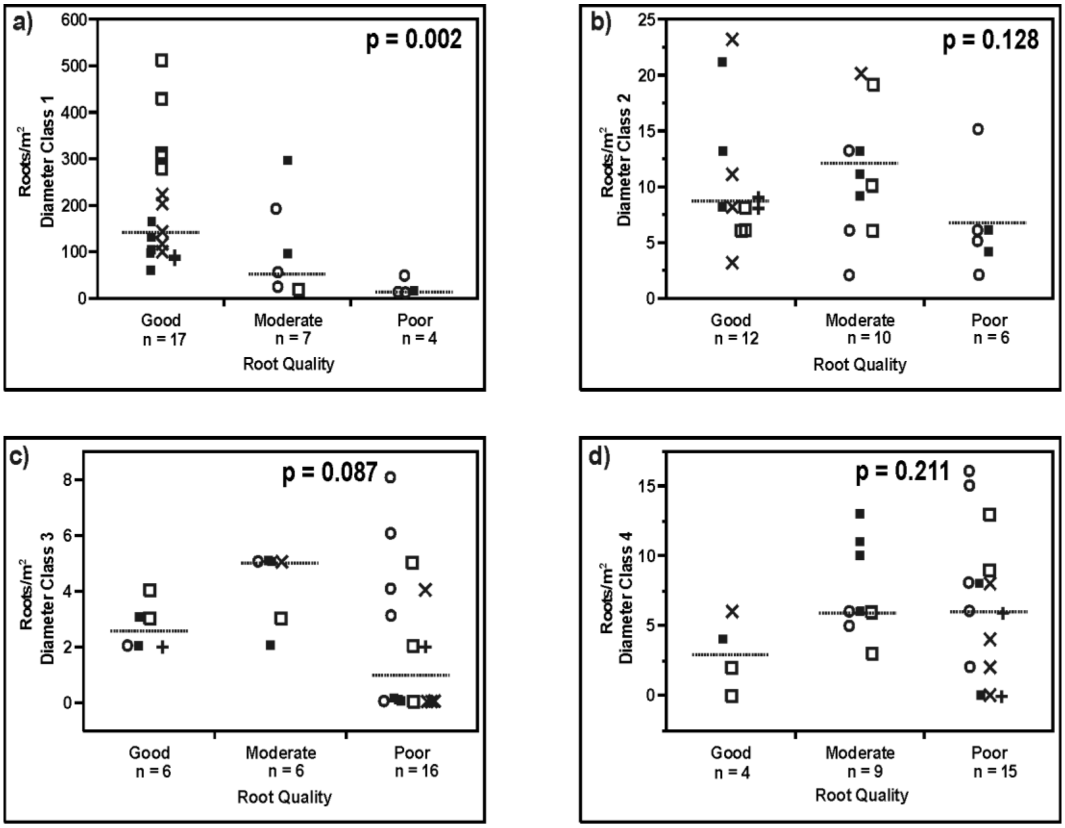



Figure 3.11: a) Poor quality roots in an 8 year old clearcut, b) Good quality roots in a 31 year old second growth stand.


Figure 3.12: Moderate root quality in an 18 year old clearcut landslide.

### 3.4.4 Root Quality and Root Density

Significant differences in root quality and root density were found for diameter class 1 using a Kruskal-Wallis test (Figure 3.13 a). Samples that have a majority of good quality roots (compared to moderate or poor quality roots) also have higher root densities. Most of the windthrow and >0-2 year old clearcuts have good quality roots with low root density (<200 roots/m$^2$) whereas 5 out of 7 second growth stands have high root density and good root quality. All samples with dominantly moderate or poor quality roots have very low root density (<100 roots/m$^2$) and are primarily in clearcuts 5-11 years old. In contrast, the second growth contains primarily high density and good quality roots.




| Root Diameter (mm) | Diameter Class |
|---|---|
| 1 to 5 | 1 |
| >5 to 10 | 2 |
| >10 to 15 | 3 |
| >15 | 4 |

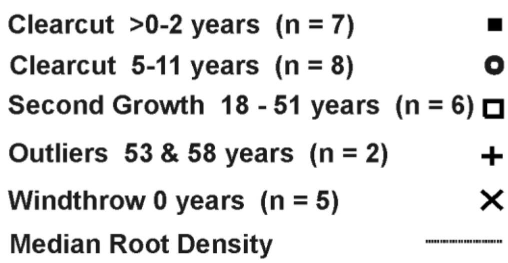



Figure 3.13: Root density vs. Root quality by age and diameter class: a) Diameter Class 1, b) Diameter Class 2, c) Diameter Class 3 and d) Diameter Class 4 (n=28).

Trends in root density were observed for poor quality roots in diameter class 2 (Figure 3.13 b). The majority of the poor quality and low density roots were in clearcuts between 5 and 11 years old.

Root classes 3 and 4 (Figure 3.13 c and d) have a large range in root density for each level of root quality. The overall trend observed was that good quality roots have a lower root density than the moderate and poor quality roots.

### 3.4.5 Root Shape Characteristics

Figure 3.14 shows plots of root density compared to a) the percentage of roots that broke when the landslide occurred, and b) the percentage of roots that are straight as opposed to crooked. Examples of a crooked and straight root are shown in Figure 3.15. An inverse relationship between the percentage of root breakage and root density was observed (Figure 3.14 a). Sidle and Ochiai (2006) found the opposite relationship. In contrast, a study by Nilaweera and Nutalaya (1999) found that the tensile strength decreased with increasing root diameter. They concluded that pull out resistance can be considered as a function of root morphology and strength. Broken roots usually indicate that frictional strength was greater than the tensile strength of the root. As root density increases there should be an increase in frictional strength since there is more root surface area (Sidle and Ochiai, 2006). Although root breakage should increase, the data shows the opposite relationship of more root pull out with increasing root density.

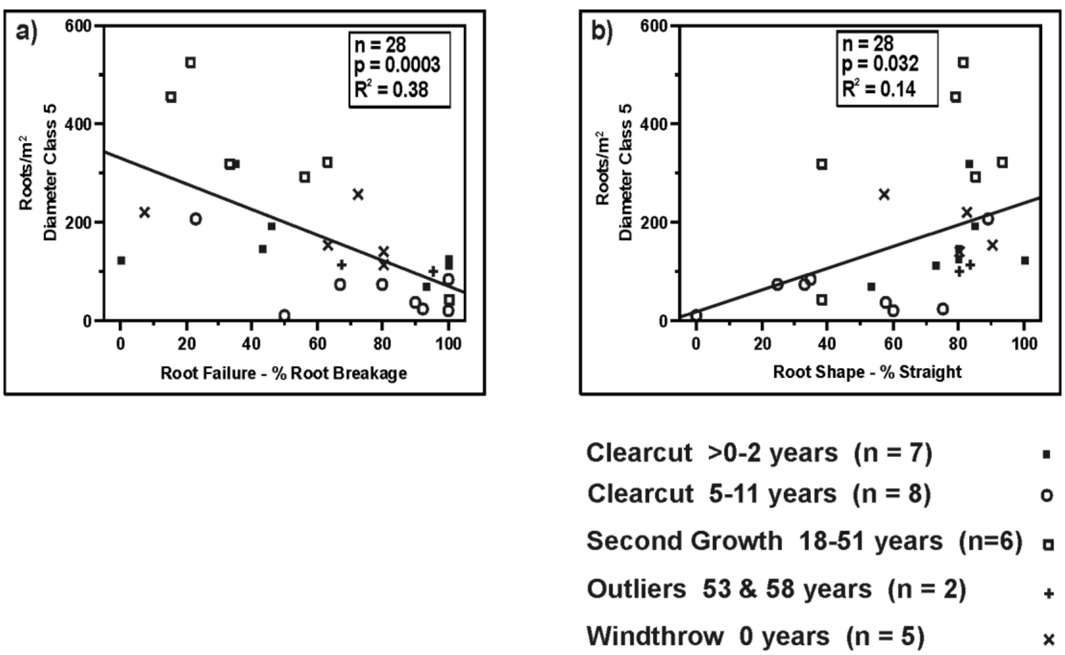



Figure 3.14: a) Root failure is the % root breakage vs. root density for all root diameters, b) Root shape is the % straight roots vs. root density for all root diameters. Diameter Class 5 = all roots diameters combined.


Figure 3.15: Straight and crooked roots within a landslide headscarp.

This trend in root breakage could be affected by root shape in combination with root density (Figure 3.14 b). Straight roots have been found to be less effective against shear failure than crooked roots (Fan and Chen, 2010; Dupuy et al., 2005). Root shape was measured by comparing the percentage straight versus crooked roots. The results show that as the percentage of straight roots increase so does the root density. The higher percentage of crooked roots within both old growth and recent clearcut landslides with low density roots could contribute to the additional root-soil resistance necessary to cause root breakage rather than root pull out (Terwilliger and Waldron, 1991). In contrast, the increased percentage of straight roots within second growth stands with high root density could cause the roots to pull out due to less frictional root resistance. A majority of the second growth stands consisted of high root density, straight roots that pulled out whereas most 5-11 year old clearcuts consisted of low root density, crooked roots, which broke in tension.

Another factor in the percentage of roots that break or pull out is the combined effect of soil shear strength and moisture (Pollen, 2007). Soil moisture and shear strength was not measured in detail at each landslide. However, soil moisture was observed and noted (eg. Well drained or poorly drained). Seepage from the landslide headscarp was also recorded during the field data collection. Soil type was recorded (eg. till or colluvium) and lab tests were conducted to classify the soil according to the Unified Soil Classification System. The data collected for soil moisture, soil density and soil type illustrated no correlation with respect to root density, quality or root pull out and breakage in the statistical analysis.

The percent lateral roots versus vertical roots were also collected at each landslide site to determine whether the roots were providing lateral or vertical tensile strength to the hillslope (Nicoll et al., 2005). Since roots were observed in the face of the landslide headscarp, a limited area was available to observe the orientation (lateral or vertical) of the root systems. It was determined in the field that an overall root orientation could be determined by observing the roots in the face of the landslide headscarp (Figure 3.16). Rarely were vertical roots observed penetrating through the failure plane into the underlying dense till or fractures in the bedrock and acting as anchors. The percentage of lateral roots ranged between 80% and 100% with a mean of 97% (Figure 3.17). Lateral roots were primarily in the upper 0.5 m of the soil profile. These lateral roots can be effective in the reinforcing the soil mass (O'Loughlin and Ziemer, 1982; Abdi et al., 2009; Fan and Chen, 2010). Determining tree species was difficult for individual roots. Consequently, no species data was collected for individual roots. Rather, an overall percentage of tree species identified from tree stumps near each landslide headscarp was recorded.

Figure 3.16: Root orientation within face of landslide headscarp. Few vertical tap roots were observed.

Figure 3.17: Extensive lateral rooting at a windthrow related landslide. Note the high number of roots pulled out rather than broken. Some of the pull out observed was related to liquefaction during high pore water pressures and not actual pull out of the roots.

### 3.4.6 Rooting Depth

A majority of roots were observed in the top 0.5 m of the soil profile and rooting depth was not proportional to soil depth. This result is similar to Schmidt et al. (2001) and Abdi et al. (2009) who determined that most roots were constrained to the upper 0.5 m of the soil profile. Root anchorage studies have also found that anchorage increases with rooting depth (Nicoll et al., 2005). There was also an increase in rooting depth as root density increased. Rooting and soil depth were recorded at each landslide site and the majority of the soil profiles consisted of colluvium or loose till overlying dense till or bedrock (Figure 3.18). Soil depths ranged between 0.2 m and 3 m with a median depth of 1.1 m whereas rooting depths ranged between 0.2 m and 0.7 m depth with a median of 0.3 m (Figure 3.19). A previous root strength study by Abe and Ziemer (1991a) in Japan illustrated that 80 to 90% of roots are located in the upper half of the rooting depth and the root volume decreases exponentially with depth. Rooting depth only increases to 0.3 m as soil depth increases to 1 m, roughly a 3:1 ratio; thus, depth to an impervious layer (dense till or bedrock) may not be a limiting factor in rooting depth. Root density (Bennett et al., 2002) and rooting characteristic of the trees (Fan and Chen, 2010) could be more important than rooting depth.


Figure 3.18: Vertical rooting restricted by dense till at 0.6 m depth. Particle size distributions showed that the till was generally a well graded sand with gravel; and the colluvium was a poorly graded gravel/sand with sand/gravel.

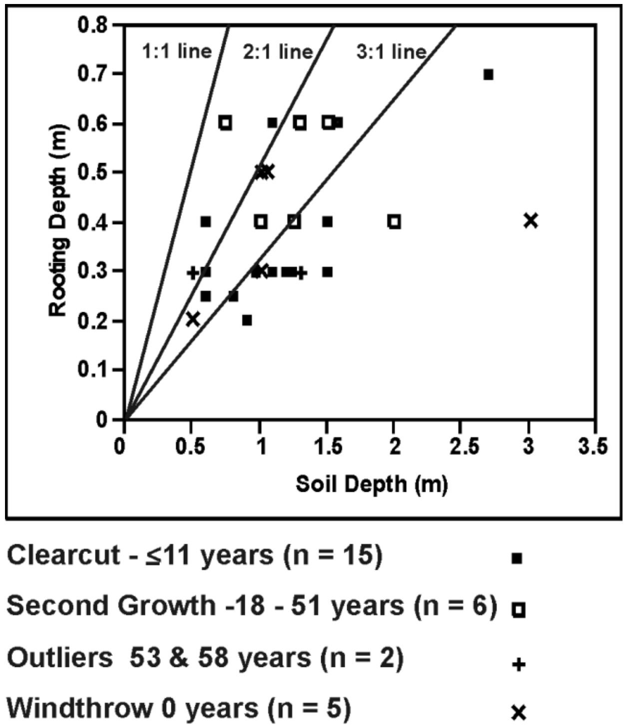



Figure 3.19: Rooting depth vs. Soil depth

There is a positive linear relationship between rooting depth and root density (Figure 3.20). Median soil depth for second growth was 1.3 m which is similar to both windthrow and clearcut landslides that had soil depths of 1.0 m and 1.15 m, respectively. The old growth roots at recent clearcuts and windthrow sample sites are lower in density and are generally restricted to the upper 0.2 to 0.4 m of the soil profile. In comparison, second growth has higher root density and rooting depths between 0.4 and 0.6 m. Therefore, increased root density probably resulted in the increased rooting depth in the second growth stands. The total percentage of roots at 1:1 slope, 2:1, 3:1, and >3:1 were 0%, 14%, 32% and 54%, respectively. The soil type varied from colluvium or dense unweathered till to loose colluvium or weathered till overlying dense till. There was difficulty in analyzing the rooting depth with respect to soil depth or root density due to the high variability in soil type at the landslide sites.

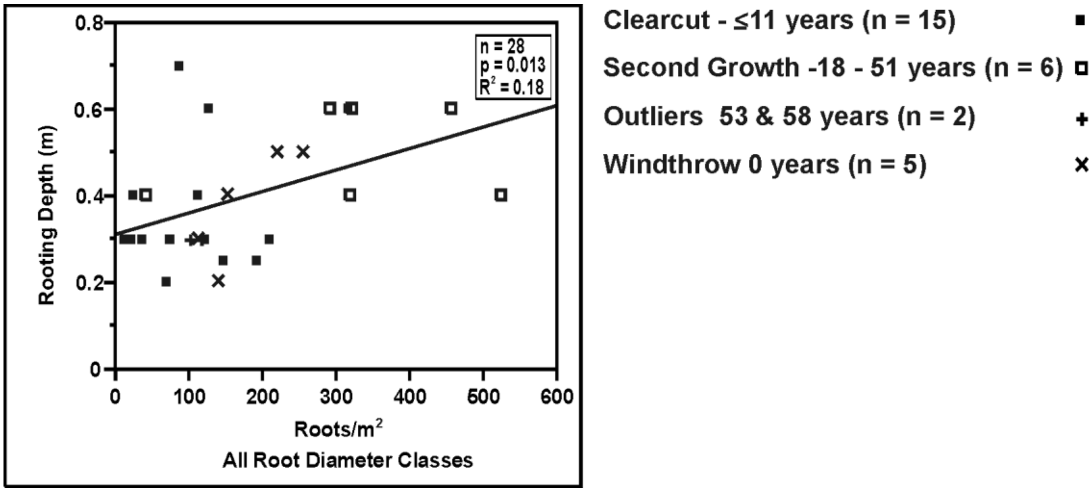



Figure 3.20: Root depth vs. Root density.

### 3.4.7 Failure Slope

Failure slope was compared between the three land uses (Figure 3.21). The failure slope was not significantly different between land uses. However, a trend was observed between the land uses where the median failure slope was 33˚ for clearcuts compared to 39˚ and 40˚ for second growth and windthrow, respectively. The clearcuts ≤11 years old have the highest density of landslides as well as the lowest failure plane slope. This could indicate that new clearcuts are less stable than second growth clearcuts or windthrow stands. The reasons for this are unclear but could be due to hydrology, a decline in root strength, or the ability of the existing tree roots in second growth and windthrow sites to reinforce the hillslope.

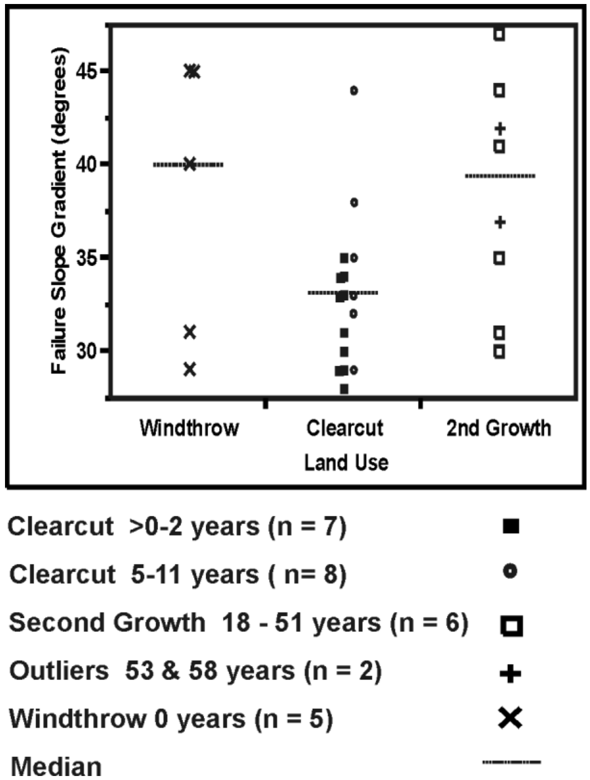



Figure 3.21: Failure slope by land use.

### 3.4.8 Forest Health

The forest health conditions were also observed and analysed. The most common forest type was balsam and hemlock followed by hemlock and cedar (Table 3.4). Hemlock and balsam are very vulnerable to root decay after harvesting (Ziemer and Swanston, 1977; Hennon and DeMars, 1997). The second growth sites consisted of Douglas-fir mixed with western hemlock or western hemlock mixed with redcedar. Douglas-fir and redcedar are the most resistant trees to root decay in BC (O'Loughlin, 1974b; Hennon et al., 1990). The higher percentage of Douglas-fir and healthy young western hemlock and redcedar trees in second growth plantations could be responsible for the higher root density and thus steeper slope angles for landslide initiation. The forests at the windthrow landslide sites consisted of western hemlock mixed with balsam or redcedar. Clearcut landslides had similar forest types to windthrow with a majority in western hemlock and balsam stands. Since the rates of decay are affected by tree species as well as the time after harvesting, the forest type is probably a contributing factor in the initiation of these landslides (Sakals and Sidle, 2004; Johnson and Wilcock, 2002).

Table 3.4: Forest type: The percentage of landslides within each land use and forest type.

| Forest Type | % Clearcuts, n=16 | % Second Growth, n=8 | % Windthrow, n=5 |
|---|---|---|---|
| Hemlock and/or Balsam | 25% (4) | 12% (1) | 60% (3) |
| Douglas-fir or Hemlock/Douglas-fir | 12% (2) | 37% ( 3) | 0% |
| Redcedar | 12% (2) | 0% | 0% |
| Hemlock and Redcedar | 50% (8) | 50% (4) | 40% (2) |

Another factor contributing to poor forest health and thus, landslide initiation is the age of the forests in this region. The old growth tree ages of the clearcut stands logged between 1997 and 2006 and windthrow stands were calculated using a digital WFP forest cover database for TFL 44. The ages of trees in these forest types were between 200 and 535 years with a mean age of 330 years. Forests of this age class and forest type can have extensive decay due to previous windthrow, disease, and fire damage (Mitchell et al., 2001; Everham and Brokaw, 1996; Dowling, 2003). Poor forest health was observed during the field data collection with many trees in existing old growth stands exhibiting fungal growth and dead or broken tops (Figure 3.22). Forest health problems in old growth contributed to low root density and reduced forest canopy (Lertzman et al., 1996; Nowacki and Kramer, 1998; Roering et al., 2003) leading to landslide initiation in windthrow and recent clearcuts.


Figure 3.22: Forest opening above a landslide initiation zone. Note: dead trees, open forest, and general poor forest health. Forest cover database indicates that this forest is approximately 320 years old.

## 3.5 Discussion

### 3.5.1 Landslide Frequency

The November 15, 2006 storm was associated with a 15 year or greater return period (Miles et al., 2008) and was probably the first major storm since logging of the most recent clearcuts (2 years old) and therefore, a first test of the slope stability. The highest landslide density for this study is within the first 2 years after timber harvesting. Two reasons for this high landslide density could be due to hydrologic changes soon after logging and the decay of fine roots <1 mm diameter. Hydrologic changes such as forest canopy removal (clearcutting) and forest gaps (reduced rainfall interception and evapotranspiration) (Kiem and Skaugset, 2003) or the crushing of soil macropores during felling and yarding (Lange et al., 2009) can have a major impact on slope stability. The loss of forest canopy was observed throughout the study with extensive areas of clearcut logging and large windthrow patches. Macropores were also observed during field data collection by root channels in the headscarps of some landslides (Figure 3.23). A total of 13 out of 48 landslide headscarps were observed with macropores.

Horel (2006) found similar results using a larger data set on northern Vancouver Island with 76% of landslides occurring within the first 5 years and 27% occurring within 1 year after harvesting. Researchers have also shown that fine roots lost within the first 2 years after logging can negatively affect the stability of slopes (Ziemer, 1981a; Dhakal and Sidle, 2003; Pollen, 2007).


Figure 3.23: Original roots have decayed allowing the development of macropores in a 27 year old second growth forest.

The second largest landslide density is in clearcuts 5 to 11 years after logging. A major contributing factor is likely root decay leading to a reduction in root reinforcement. The harvest age 5 to 11 years has been shown as a root density and root strength low point in many studies (Ziemer, 1981a; Burroughs and Thomas, 1977; Sidle and Ochiai, 2006; Ammann et al., 2009). Although root strength was not measured, the root density (Figure 3.6 a, b and d) and root quality (Figure 3.10 a and b) show minima during the same time periods as previous root strength studies.

For landslides in clearcuts ≥18 years old, low root density is a minor contributing factor in landslide initiation. The large number of landslides in second growth could have resulted from high winds moving the trees and the root systems during the storm. The movement of the roots may have resulted in root breakage, the loss of soil-root cohesion, or the build up of high pore water pressures leading to slope failures.

### 3.5.2 Root Density

The root density decreases exponentially in diameter classes 1 and 2 between 0 and 11 years and increases linearly between 11 and 51 years after harvest (Figure 3.24 a). These results are similar to that of Ziemer (1981a) and Sidle (2005) since they both have a root density minima at approximately 10 years after harvesting. Ziemer (1981a) shows re-growth of roots levelling off at around 25 years (Figure 3.24 b), whereas the current study shows a continued increase in root density after 25 years.

The small roots are most vulnerable to decay due to their small diameters, since 50% to 80% of the original root reinforcement for roots ≤10 mm in diameter may be lost within the first 2 years after logging (O'Loughlin, 1974 a; Ziemer and Swanston, 1977; Burroughs and Thomas, 1977; and Ziemer, 1981a and b). These previous studies have found that a major contributing factor for landslides in clearcuts ≤ 2 years old is root decay. The rapid decline in root density confirms that the smallest root diameters are the most important roots responsible for slope stability (Burroughs and Thomas, 1977; Ziemer, 1981a; Johnson and Wilcock, 2002).

The linear increase in root density for diameter classes 1 and 2 between 11 and 51 years after harvest (Figure 3.6 a, b) is likely the effects of healthy growing plantations consisting of Douglas fir and hemlock. The second growth stands have densities that are nearly 2.5 times higher than the old growth windthrow stands. These second growth forests consist of healthy trees that are growing vigorously and have much higher root densities than the old growth forests. Old growth stands between 200 and 500 years old are commonly infected with root disease due to wind, fire, and pest damage. Root disease is probably a major factor responsible for the low root density in old growth compared to second growth stands (Nowacki and Kramer, 1998; Dowling, 2003). However, logic would suggest that root density would not continue to increase indefinitely. Consequently, at some unknown age root density should level off and even decrease. Root data collection from older second growth stands, between 50 and 100 years old, would be required to determine where root density levels off and/or decreases.

The largest roots in the second growth stands were still visible 50 years after logging, although they may provide only minimal support for slope stability due to their poor quality. There was no significant difference in diameter class 3 and 4 with time after harvest. This is similar to other studies, which also found that the smaller root diameters are the most sensitive to root decay after logging (Burroughs and Thomas, 1977). The larger roots probably require a longer period of time to decay and therefore, are not detected in the statistical analysis.

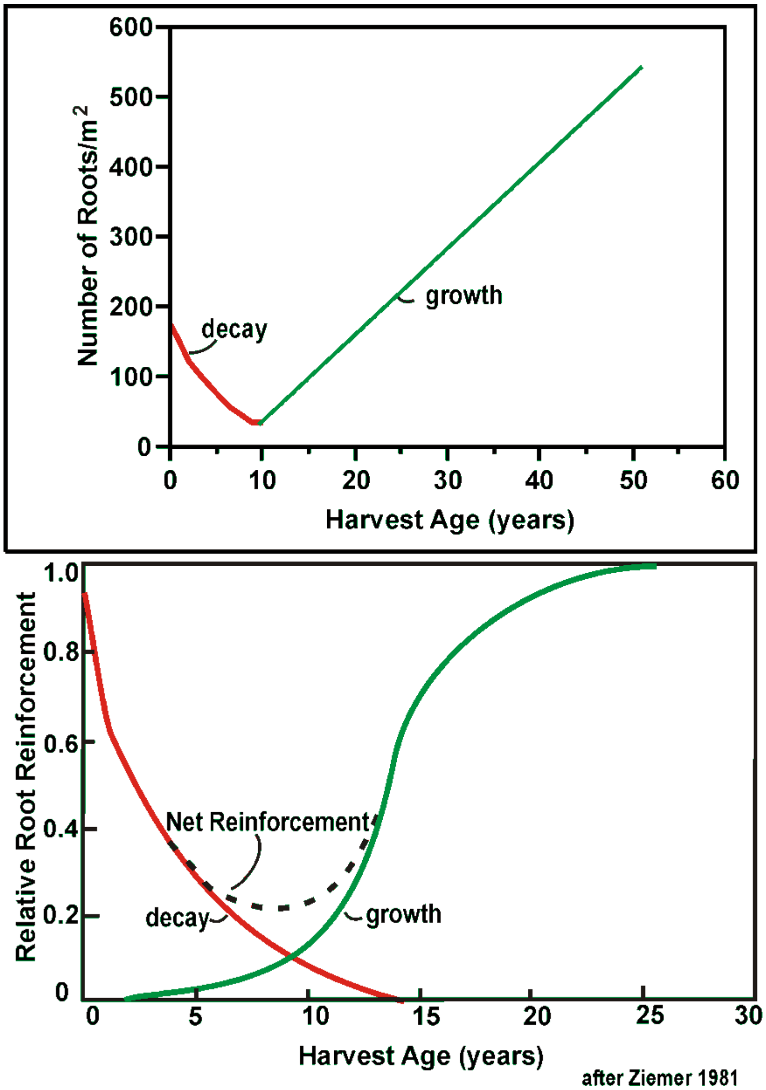



Figure 3.24: a) Change in root density with time for southwestern Vancouver Island study b) shows a conceptual model of relative root reinforcement after harvest; after Ziemer 1981a.

The RAR was compared between three land uses; clearcuts (1-11 years), second growth (18-51 years), and windthrow (unlogged old growth) (Figure 3.25). The range of RAR for windthrow is similar to clearcuts but the second growth has a maximum RAR that is twice that of windthrow and clearcuts. This study's minimum value for second growth is similar to clearcuts if the two outliers and one of the 18 year old clearcuts (which was in an area of low plantation density) are excluded. These findings are in contrast to Schmidt et al. (2001) who found that natural forests (>200 years) on the Oregon Coast have a higher RAR than clearcuts (<11 years) or industrial/second growth forests, (43 to 123 years). This difference could be due to the health of the old growth on the British Columbia Coast compared to the Oregon Coast. British Columbia forests are further north and can experience cooler temperatures contributing to poor forest health such as frost damage. Previous research involving windthrow modelling has focussed on the effects of wind on tree damage along clearcut boundaries (Mitchell et al., 2001; Yang et al., 2006). Windthrow may not be comparable to old growth due to different growing and site conditions. For the purposes of this study, we assumed that windthrow was equal to old growth stands by selecting windthrow sites with deeper soils and better growing conditions. Overall, the root density in diameter class 1 for windthrow is much lower than second growth stands and is actually more similar to clearcuts ≤11 years old. There was no significant difference between land uses and root density for the other three diameter classes. The smallest diameter class gives a better comparison between land uses probably due to the smaller roots being more sensitive to decay after logging. This also shows the importance of the smallest root diameters when determining differences in root densities between land uses. The difference in root density is better illustrated in the smaller diameters than when all root diameters are compared.

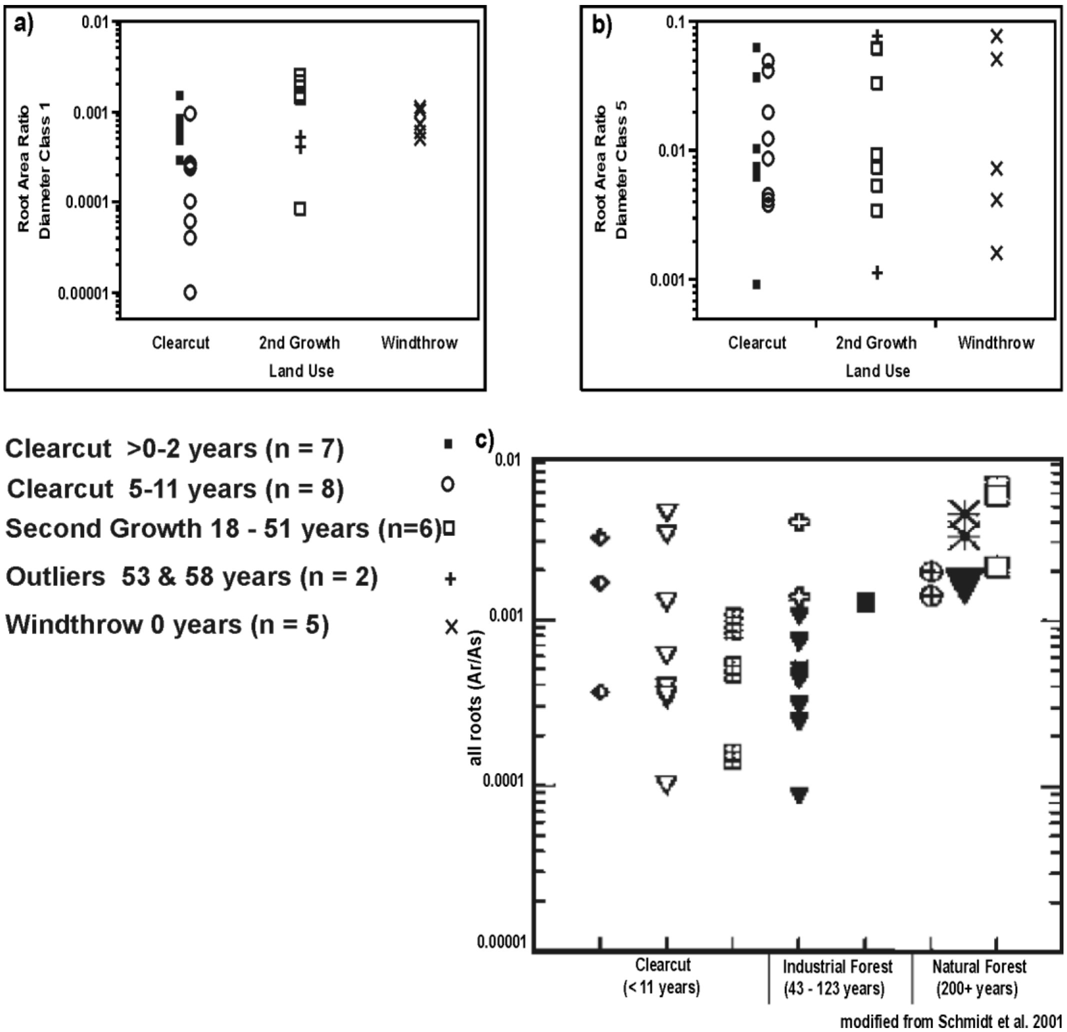



Figure 3.25: Root area ratio at log scale compared between three land uses for a) diameter class 1 (1-5 mm), b) diameter class 5 (all roots), and c) Schmidt et al. 2001 (all roots).

### 3.5.3 Root Quality

Soils in 5 to 11 year old clearcuts have low root densities and most roots are of poor quality. The poor quality roots during minima in root density can accelerate landslide densities. Because of the poor root quality and density in old growth, cutting these forests causes an even greater reduction in root strength; thus, recent clearcuts have an increased risk of slope failure.

The youngest clearcuts have had little time for decay therefore, a small number of poor quality roots were observed. The second growth stands have a variety of different quality roots. The poor quality roots reflect the longer time required for larger roots to decay and the good quality roots are a sign of re-growth of some larger roots.

A majority of the >10 mm diameter roots in the windthrow sites were poor quality. This could be due to factors such as windthrow occurring on poor growing sites around the perimeter of clearcuts or the declining health of old growth stands. Since five windthrow landslides were selected from sites that were similar to clearcuts, the poor growing conditions should be a minor component. The health of the trees within the old growth forests are the most significant factor contributing to poor quality roots in windthrow. The old growth has been subject to between 200 and 500 years of damage due to wind (Pearson, 2001), disease (Nowacki and Kramer, 1998) and fire resulting in unhealthy and damaged root systems. The smaller roots <10 mm can recover more readily than the larger roots therefore the larger roots will show more signs of damage and decay.

Roots fail by two main mechanisms: either by breaking due to the shear induced tensile forces being exerted on the roots or pull out where the soil–root bond is lost and the roots slip through the soil. This study shows a relationship where root breakage increases with a decrease in root density. This increase in breakage with lower root density is contrary to previous studies (Sidle and Ochiai, 2006) and could be due to the abundance of crooked roots in low density sites. The number of straight roots increase with an increase in root density. The increased number of crooked roots that are present compared to straight roots could create more frictional resistance and therefore, more breakage in the old growth root systems (Fan and Chen, 2010; Dupuy et al., 2005). Old growth roots were observed to be more crooked in shape; this increase in frictional resistance makes them more prone to root breakage than pull out.

### 3.5.4 Rooting Depth

The root density increase in second growth stands is probably due to the vigorous root growth relative to the less healthy, slower growing root systems of the clearcut and windthrow related landslides. The second growth also contains a higher number of small diameter roots that can grow deeper into the soil (Figure 3-20). Since few roots were observed deeper than 0.5 m and more than 85% of the roots were lateral, the main method of root reinforcement was lateral not vertical (O'Loughlin and Ziemer, 1982; Nicoll et al., 2005).

### 3.5.5 Factors Affecting Slope Stability

Our results showed that clearcut landslides occur at a lower slope angle than second growth and windthrow landslides. The roots in the 5 to 11 year old clearcuts have advanced decay and a sharp decrease in root reinforcement. The decrease in root reinforcement reduces the shear strength resulting in landslides on lower slope angles (Nilaweera and Nutalaya, 1999). In contrast, the windthrow and second growth landslides occur on steeper slopes, the result of higher root density contributing to increased shear strength.

Trees in old growth forests in this region of southern Vancouver Island are between 200 and 500 years old. Many old growth forests, between 200 and 500 years old, can experience numerous wind and fire events and disease infestations creating forest canopy gaps (Sakals et al., 2006). Rather than starting from primary succession and an even aged stand as with fire, there is a tendency with succession, wind and disease to produce multi-aged stands where trees have variable ages. Thus, the forest has poor health trees with root disease problems and a component of young vigorous trees. Forest diseases can eventually kill the host tree. The root decay process probably starts years before harvesting since old growth forests have experienced centuries of succession, wind damage and disease.

## 3.6 Conclusions

This landslide study focussed on logging related landslides and was completed in the Klanawa, Sarita, and Nitinat River valleys on southwestern Vancouver Island. The conclusions regarding landslide density, root density and root quality are as follows:

1) A majority (67%) of open slope landslides occur within 11 years after harvesting. In the first 2 years after logging, 27% of landslides occur and an additional 40% initiate between 4 and 14 years. This result is similar to other studies where high landslide densities occurred within the first 10 to 20 years after logging (Ziemer and Swanston, 1977; Burroughs and Thomas, 1977; Ziemer, 1981a) or tree mortality (Johnson and Wilcock, 2002; Ammann et al., 2009). Landslides between 3 and 15 years after harvest are likely attributed to low root density and poor root quality. The low root density and quality results in lower root strength and a decrease in soil shear strength. Landslides in the first two years after harvesting may also be influenced by hydrologic changes and were observed by the presence of macropores in old root channels.

2) This study confirms conclusions from previous studies that root diameters ≤10 mm have the highest rate of decay. The largest decline is in the 1-5 mm diameter class (class 1) where there is an exponential decay rate in the first 11 years after logging. These (fine) root systems also regenerate rapidly. In

second growth forests logged between 18 and 51 years there is a linear increase in root density. The root density at 51 years old is nearly 2.5 times the density of the original old growth forest.

3) The root quality data corresponds to the results of the root density analysis. Clearcuts harvested between five and eleven years ago have the lowest root quality for roots <10 mm diameter. Other age classes have a majority of good or moderate quality roots for roots <10 mm diameter. Root diameters >10 mm have mostly moderate and poor quality roots. Root quality and root density trends were difficult to detect for larger roots.

4) The root density in old growth forests as observed in the windthrow and recently harvested clearcuts ≤11 years old is significantly different from those of 50 year old second growth stands. This is probably due to declining forest health in old growth stands and the improved health and vigorous growth of second growth stands. Old growth stands are commonly in poor health and there was evidence of previous wind damage and disease.

5) Forest health has a major influence on root density, root quality and root characteristics. Old growth forests between 200 and 500 years old have a long history of wind damage and disease that has negatively impacted the tree roots resulting in lower root density and quality. Second growth stands regenerating between 18 and 51 years ago have developed good quality, higher density root systems. The managed plantation density, tree species selection and better site conditions have probably allowed for better root growth (Dowling, 2003).

6) The maximum depth of roots is independent of soil depth. This maximum rooting depth is probably due to increased nutrient supply in the upper soil

horizons as well as looser, weathered soil in the top 0.5 m allowing easier root growth. Therefore, vertical rooting has a minor influence on slope stability and consequently, lateral roots are the most important form of rooting on hillslopes. Rooting depth also increases with an increase in root density and harvest age, which is primarily due to increased forest health in second growth stands.

The storm of November 15, 2006 provided an excellent opportunity to study the influence of roots on open slope landslides in recent clearcuts, second growth, and old growth. Roots are an important factor in slope stability and further study is warranted on Vancouver Island.

# 4: Basal Organic Layer Properties on Southwestern Vancouver Island, British Columbia

## 4.1 Introduction

Researchers and terrain stability professionals in coastal British Columbia have observed a basal organic rich layer, hereafter referred to as “organic layer” located at depth in the mineral soil profile. Only limited pedologic research on this organic layer has occurred over the past 40 years in Coastal British Columbia (Lewis and Lavkulich, 1972; Sanborn and Lavkulich, 1989a and b; and Martin and Lowe, 1989) and limited research has been conducted on the organic layer geotechnical properties (Nagle, 2000). Sanborn and Lavkulich (1989 a) examined organic layers on Vancouver Island near Bamfield, BC.

The organic layer has been identified as a basal organic matter rich zone in Ferro-Humic Podzols (Sanborn and Lavkulich, 1989b). They believe the basal organic layer develops due to dying and decaying roots over centuries with only a few living roots actually identified (Sanborn and Lavkulich, 1989b). The geotechnical and pedologic properties of a Folisol soil were identified in British Columbia by Lewis and Lavkulich (1972) and Nagle (2000). Folisols are an organic soil that develops in forest soils at the surface and not at depth such as the basal organic rich layer in this current study. Geotechnical and statistical analysis was also conducted on Folisols by Nagle (2000) to identify shear strength parameters and site characteristics for the soil.

Development of the organic layer has also been attributed to poor drainage conditions along dense till or bedrock (Martin and Lowe, 1989). A majority of the organic deposits have >17% Organic Carbon (or >30% organic content) by weight (Sanborn and

Lavkulich, 1989b) and are defined as organic soils (NRC, 1998). The organic layer root mats were observed to be between 1 cm and >40 cm thick and located at depths between 0.5 m and 1 m below ground surface (Sanborn and Lavkulich, 1989a,b).

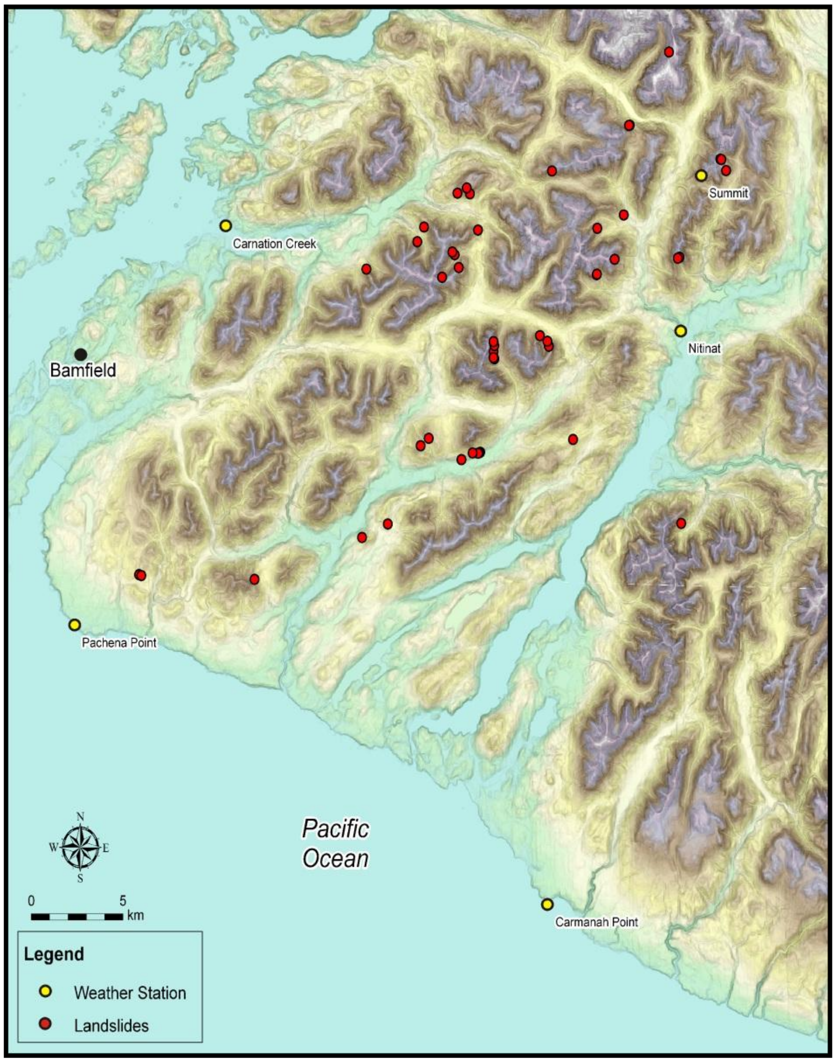



Figure 4.1: Project area map showing locations of 48 landslides investigated during the field study. Thirty locations were identified with an organic layer overlying the landslide failure slope.

Southwestern Vancouver Island experienced several large storm events during fall 2006 and winter 2007, which triggered over 230 landslides (Figure 4.1). The storm event on November 15, 2006 caused a majority of the landslides in the Klanawa, Sarita, and Nitinat River Valleys, and was accompanied by high wind gusts in excess of 100 km/hr. and rainfall exceeding 200 mm in 24 hours. Forty-eight open slope cutblock and windthrow-associated landslides were investigated in the field during the summer of 2007. The objective of this chapter is to identify terrain and soil properties indicative of the basal organic layer.

The goals of this chapter are to:

1) determine geotechnical properties including the angle of friction, moisture and organic content, and particle size of the organic layer; and

2) identify terrain and locations where the organic layer develops.

## 4.2 Setting

The research area is located on southwest Vancouver Island near the community of Bamfield, approximately 160 km west of Vancouver, BC. The project area includes the Nitinat, Klanawa and Sarita River watersheds and is bounded to the west by Pacific Rim National Park and the Pacific Ocean, to the south and east by the Cowichan Lake watershed and Carmanah Provincial Park, and to the north by Alberni Inlet. A majority of the area lies within Western Forest Products (WFP) and Teal Cedar Products Tree Farm Licences (TFL), which include TFL 44 and 46, respectively, as well as other crown land licences such as Forest Licences and BC Timber Sales. Small parcels of private land also exist, primarily at low elevations, in the Sarita and Nitinat River valleys.

The Vancouver Island Ranges are the dominant mountain range on Vancouver Island and trend northwest southeast through the study area. Pleistocene glaciations have carved U shaped valleys and fiords throughout the area and deposited thick till and glaciofluvial sediments on lower to middle slopes (Holland, 1964). Colluvium dominates the upper valley slopes and fluvial deposits are present on the valley bottoms.

Most of the bedrock geology is Jurassic, consisting of granitic intrusive rocks from the Island Plutonic Suite, West Coast Crystalline Complex, and volcanic rocks from the Bonanza Group (Massey et al., 2005). Lesser amounts of Upper Eocene and Triassic sedimentary rocks from the Vancouver and Carmanah Groups also exist in the area.

The climate is wet and humid with cool summers, mild winters, and low amounts of snowfall (Green and Klinka, 1994). Major rainfall events from moist Pacific air masses occur between October and March, and are associated with significant landslide activity (Jakob, 2000). The study area contains two variants of the Coastal Western Hemlock (CWH) Biogeoclimatic Zone: 1) the submontane very wet maritime variant (CWHvm1) between sea level and 600 m elevation and 2) the montane very wet maritime variant (CWHvm2) between elevations of 600 m and 1000 m (Green and Klinka, 1994). The CWH forests are dominated by tree species such as western hemlock (*Tsuga heterophylla)*, amabilis fir or balsam (*Abies amabilis)*, western redcedar (*Thuja plicata)*, and lesser amounts of Douglas-fir (*Pseudotsuga menziesii),* and Sitka spruce (*Picea sitchensis).* The average annual precipitation for the Nitinat River Hatchery weather station is 4000 mm with mean temperatures ranging between 3° and 17°C (Figure 4.2).

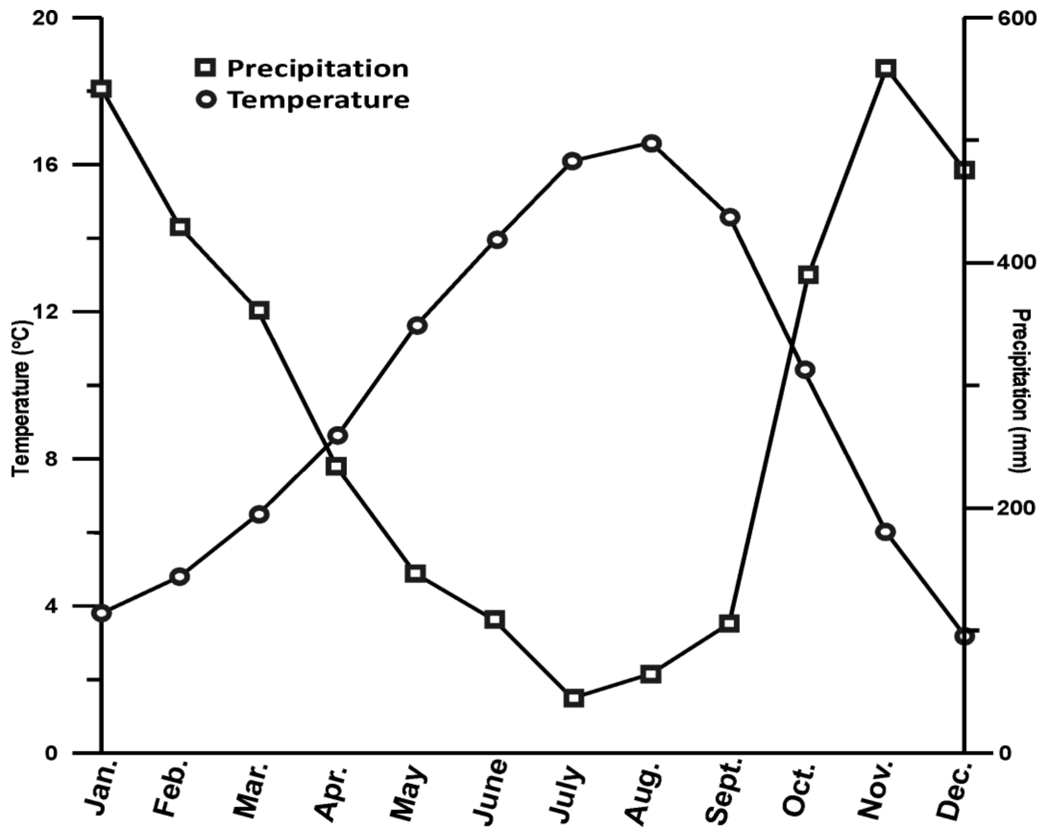


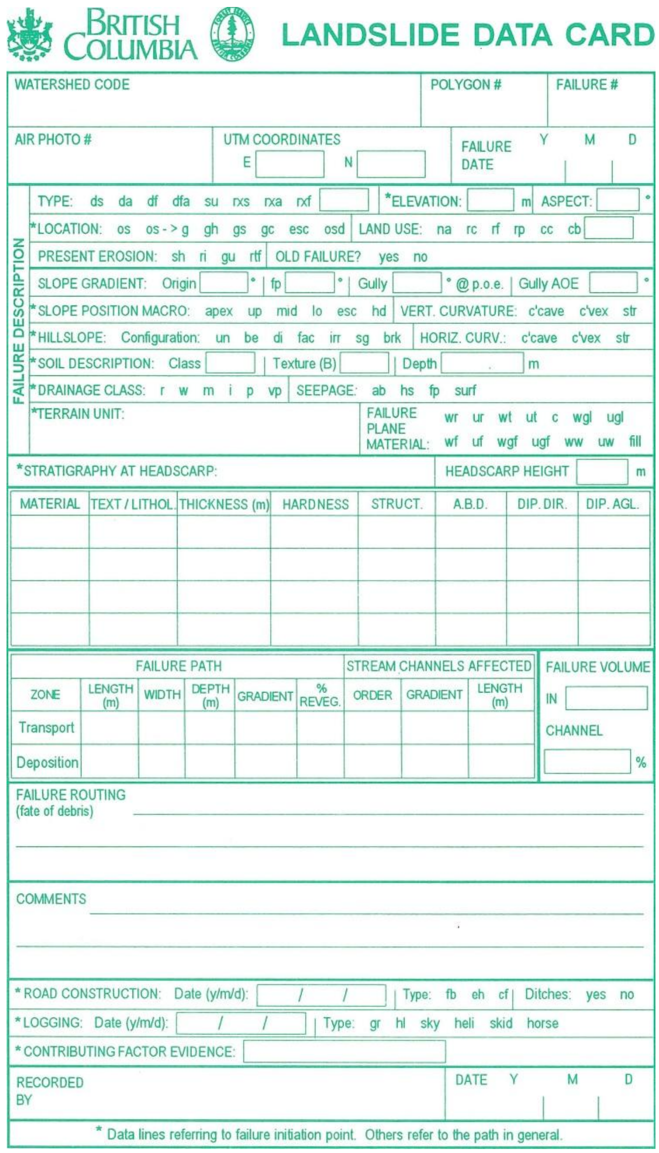

Figure 4.2: Environment Canada monthly climate normals for Nitinat River hatchery (Environment Canada, 2009b).

## 4.3 Methods

### 4.3.1 Sample Design and Data Collection

Forty-eight landslides were visited in the Sarita, Klanawa, and Nitinat watersheds after the winter storm events of 2006/2007. As part of a larger study, data for a basal organic layer was collected at each landslide where the organic layer was present. In addition, the presence and thickness of any organic layer at the landslide failure slope was recorded. Organic layer samples were collected from 11 landslides for laboratory testing.

Terrain, soil and root density data were collected in the field for 15 clearcuts, 8 second growth and 18 windthrow associated landslides the remaining 7 landslides, 1 clearcut and 6 windthrow, were unsafe and no detailed initiation zone soil data was collected. The immediate area above the landslides was examined to ensure there was no road drainage influence above the landslide initiation zone. Terrain attributes such as slope gradient, soil depth and type, slope curvature and position, aspect, drainage, landslide dimensions, and elevation were recorded on a BC Forest Service Landslide Data Card (Figure 4.3). The landslides were located using landslide event reports and reconnaissance maps from WFP.



BRITISH COLUMBIA LANDSLIDE DATA CARD

WATERSHED CODE | POLYGON # | FAILURE #

AIR PHOTO # | UTM COORDINATES E N | FAILURE DATE Y M D

FAILURE DESCRIPTION

TYPE: ds da df dfa su rxs rxa rxf | *ELEVATION: m ASPECT: °

*LOCATION: os os - > g gh gs gc esc osd | LAND USE: na rc rf rp cc cb

PRESENT EROSION: sh ri gu rtf | OLD FAILURE? yes no

SLOPE GRADIENT: Origin ° | fp ° | Gully ° @ p.o.e. | Gully AOE °

*SLOPE POSITION MACRO: apex up mid lo esc hd | VERT. CURVATURE: c'cave c'vex str

*HILLSLOPE: Configuration: un be di fac irr sg brk | HORIZ. CURV.: c'cave c'vex str

*SOIL DESCRIPTION: Class | Texture (B) | Depth . m

*DRAINAGE CLASS: r w m i p vp | SEEPAGE: ab hs fp surf

*TERRAIN UNIT: | FAILURE PLANE MATERIAL: wr ur wt ut c wgl ugl wf uf wgf ugf ww uw fill

*STRATIGRAPHY AT HEADSCARP: | HEADSCARP HEIGHT m

| MATERIAL | TEXT / LITHOL. | THICKNESS (m) | HARDNESS | STRUCT. | A.B.D. | DIP. DIR. | DIP. AGL. |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

| FAILURE PATH | | | | | | STREAM CHANNELS AFFECTED | | |
|---|---|---|---|---|---|---|---|---|
| ZONE | LENGTH (m) | WIDTH | DEPTH (m) | GRADIENT | % REVEG. | ORDER | GRADIENT | LENGTH (m) |
| Transport | | | | | | | | |
| Deposition | | | | | | | | |

FAILURE VOLUME
IN
CHANNEL
%

FAILURE ROUTING (fate of debris)

COMMENTS

* ROAD CONSTRUCTION: Date (y/m/d): / / | Type: fb eh cf | Ditches: yes no

* LOGGING: Date (y/m/d): / / | Type: gr hl sky heli skid horse

* CONTRIBUTING FACTOR EVIDENCE:

RECORDED BY | DATE Y M D

* Data lines referring to failure initiation point. Others refer to the path in general.

Figure 4.3: BC Forest Service Landslide Data Card (MOFR, 1996).

The following laboratory tests were conducted to determine the geotechnical properties of the organic layer: moisture content, Atterburg limits (liquid and plastic limits), particle size analysis, loss on ignition (LOI), Hydrogen Peroxide, x-Ray diffraction, and direct shear tests. All laboratory testing was completed at Simon Fraser University except for X-ray diffraction analysis and direct shear tests which were completed at the

University of British Columbia (UBC) and British Columbia Institute of Technology (BCIT), respectively.

Moisture content was undertaken for liquid limits and loss on ignition using ASTM D4254. An oven temperature of 60$^{o}$C was used for the organic layer samples to reduce the potential soil mass loss by burning off the organic matter.

The liquid limit test, British Standard (BS) 1377, was conducted using the cone penetrometer method (definitive or multipoint method). The plastic limit test was also conducted using BS 1377. Atterburg limits (liquid and plastic limits) were conducted using non-dried samples and oven-dried samples. The non-dried samples for the organic layer were not sieved, rather the soil was visually inspected and gravel size particles (>4.75 mm) were removed prior to testing.

Loss on ignition and Hydrogen Peroxide tests were used to burn off organic matter. Loss on ignition tests were conducted to determine the organic content by percent weight using the methods by Kalara and Maynard (1991). Hydrogen Peroxide was also used to determine the organic content and prepare samples for X-ray diffraction using the methods by the USGS (2001). Burning off the organic matter also allowed the use of the Mastersizer 2000 to determine the particle size distribution of the inorganic fraction of the organic layer.

Particle size analysis was conducted on the inorganic fraction of the organic layer using ASTM D422. Classification of soil for engineering purposes was conducted using the Unified Soil Classification System (USCS) with regard to ASTM D 2487. The Mastersizer 2000 laser diffractometer was used to determine the particle size distribution of the inorganic (mineral) soil fraction of the organic layer for particle sizes less than 2 mm after the organic portion was burned off using LOI and Hydrogen Peroxide. The methods outlined in Sperazza et al. (2004) were used for the Mastersizer 2000 analysis.

The mineral soil fraction remaining from the LOI and Hydrogen Peroxide tests were dry sieved. Dry sieving was conducted to ensure particle sizes greater than 2 mm were not entered into the Mastersizer 2000.  The Mastersizer 2000 was used to determine fine to medium sand, silt and clay content instead of the hydrometer method. The hydrometer method was not used on the inorganic soil fraction from the loss on ignition and hydrogen peroxide tests since the sample sizes were too small. The coarse sand that was sieved from the samples prior to using the Mastersizer 2000 was included in the final particle size analysis of the inorganic soil fraction for the organic layer.

X-ray diffraction (XRD) was conducted on the organic layer after burning off the organic matter with loss on ignition and hydrogen peroxide tests. X-ray diffraction testing and analysis was completed at the University of British Columbia (UBC), Department of Earth and Ocean Sciences. The methods used by UBC for XRD analysis are attached in Appendix C.

Direct shear tests of soils under consolidated drained conditions were conducted using ASTM D 3080. Direct shear testing was completed at the BCIT in April 2009 (Figure 4.4). All samples were pre-consolidated for 45 minutes prior to conducting the direct shear test. Three different loads of 5, 10 and 15 kg were applied for the direct shear tests and pre-consolidated to equal an in-situ normal stress of 13.4, 27.4 and 40.8 kPa, respectively. The loads applied simulated approximate overlying mineral soil depths of 0.7, 1.4 and 2.0 m assuming a soil unit weight of 20 $kN/m^3$. The loads and corresponding soil depths were considered representative of the observed field conditions regarding soil depth and soil type.

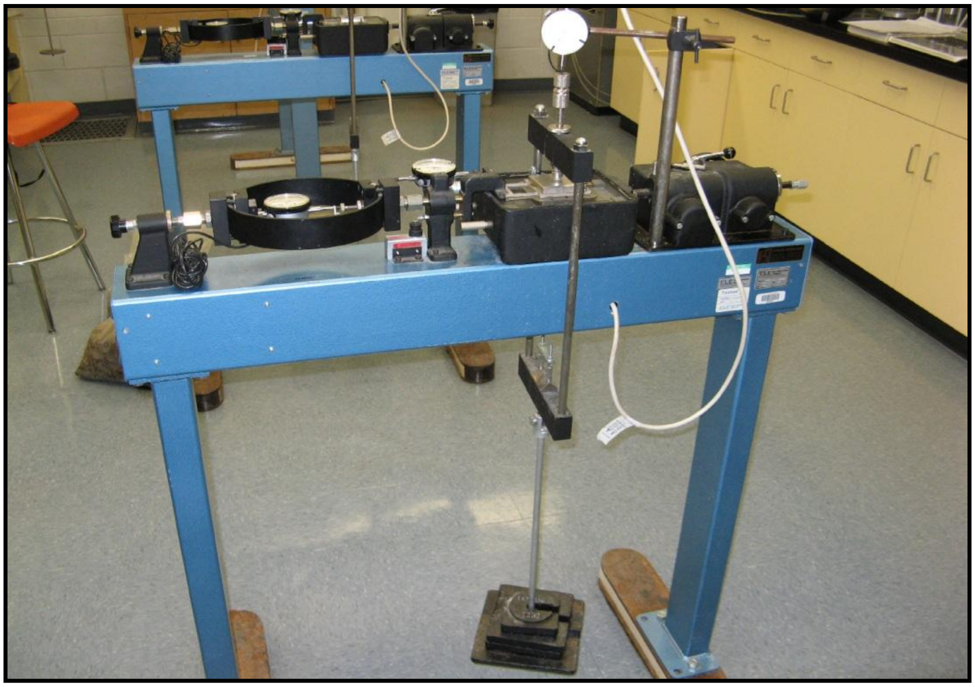


Figure 4.4: Direct shear testing apparatus for determining friction angle of organic layer samples conducted at BCIT.

### 4.3.2 Data Analysis

A univariate statistical analysis was conducted using Kruskall-Wallis tests and $X^2$ tests. A significance level of $P \leq 0.05$ was considered significant and therefore evidence to reject the null hypothesis.

Contingency tests were conducted when there was nominal or ordinal data for both the independent and dependent variables. A two-tailed $X^2$/ Fisher's Exact test or a Pearson $X^2$ was used for the contingency tests. Due to the small field data set (n=48) a majority of these tests were suspect due to 20% of cells having counts less than five. Although 30 landslides were identified with an organic layer, the total number of landslides analysed with or without the presence of an organic layer was 48. These cases were identified with an asterisk in the summary tables. A significance level of $P \leq 0.10$ was considered significant and therefore evidence to reject the null hypothesis.

Unlike the t-tests, the significance level for the contingency tests was $P \leq 0.10$, as the data required more flexibility (Wolter et al., 2010).

## 4.4 Results and Discussion

### 4.4.1 Organic Layer Characterization

The physical characteristics of a basal organic rich layer identified at the failure slope of 30 out of 48 landslide sites was analysed. The organic layer was observed between a depth of approximately 0.2 m and 3 m below ground surface with a median depth of 1 m. The organic layer thickness was between 0.05 m and 0.4 m with a median thickness of 0.1 m.

The organic layer was visually identified as highly organic in the field. The layer has a typically dark brown to black colour, a spongy feel, a fibrous texture, and an organic odour. According to the Unified Soil Classification System (USCS), soils that are highly organic should be classified by visual observation as "highly organic soil and peat" (Pt). Although the organic layer did not contain peat, there was evidence of roots and humus (organic matter) in the deposit. The British Soil Classification System (BSCS) has a similar classification of Pt for highly organic soils.

The basal organic layer was primarily underlain by bedrock and/or unweathered dense till with weathered loose till or colluvium overlying the organic deposit (Figure 4.5 and Figure 4.6). A soil profile of a typical landslide site illustrates the location of the basal organic layer relative to the overlying and underlying soil/bedrock layers (Figure 4.7).

There was some inorganic soil fraction within the organic layer due to the layer developing at depth within a predominantly inorganic mineral soil. Particle size analysis of the overlying and underlying mineral soil was completed for a majority of the landslide headscarps where there was access. The particle size distributions for loose weathered till, colluvium and dense unweathered till are illustrated in Figure 4.8. Particle size distributions showed that the weathered till was generally a well graded sand with gravel/with silt. The colluvium was a poorly graded gravel with sand. Finally, the unweathered till, underlying the organic layer, was a well graded sand with gravel. Based on the particle size analysis, the inorganic fraction of the organic layer, which visibly contains trace sand and trace gravel, appears to be derived from the overlying and underlying mineral soil layers.

Organic layer deposits were also observed in old root cavities positioned vertical or oblique to the failure slope surface (Figure 4.9). Previous studies named these organic layers parallel to the failure slope “root mats” and the oblique or vertical organic deposits “root channels” (Sanborn and Lavkulich, 1989a; Martin and Lowe, 1989). During the field work some roots were observed within the organic layer deposits. The organic layer deposit filled root channels between approximately 5 and 20 cm in diameter. Few live roots were observed within the organic layer and old root channels. The root channels are locations where old roots have decayed. This was particularly relevant to clearcuts and old growth forest where trees die and the roots decay leaving the root channels. The root channels were later infilled by organic accumulation from decaying roots or the translocation of organic matter from the upper soil horizons (Sanborn and Lavkulich, 1989a).

The moisture content of the organic layer in the field was generally wet, with water observed flowing out of the organic layer at some of the landslide sites. Water was easily squeezed out of the organic layer when handled in the field. The organic layer was fibrous to greasy and sometimes sticky when handled. It would leave a brown to black stain on the hand after handling.

Macropores were observed in the headscarps and failure slopes of 35% of the landslides in this study (Figure 4.10 a). Macropores develop in several ways such as; the deterioration of roots, animal burrows, and cracks within the soil matrix (Aubertin, 1971). A majority of the macropores observed were probably root channels from decaying roots due to clearcutting and old growth tree mortality. These root channels can act as conduits for subsurface water flow and efficiently route water downslope reducing pore water pressures and, therefore, increasing slope stability (Ziemer, 1992). Soil rooting depth and diameter of the roots can also increase the amount of downward subsurface flow (Devitt and Smith, 2002). Old root channels were filled with organic layer deposits due to the translocation of upper soil horizons and the decay of tree roots at several sites (Figure 4.10 b). The macropores can also collapse and plug due to timber felling and yarding or windthrow events (Campbell et al. 2010). The plugging of the macropores can cause an increase in slope instability.

Organic layer deposits were also observed in bedrock fractures present along the failure slope at a number of landslide sites (Figure 4.11). The plugging of rock fractures can result in high pore water pressures similar to plugged macropores.

Figure 4.5: Basal organic layer approximately 40 cm thick overlying bedrock.


Figure 4.6: Organic layer overlying till and further overlain by colluvium in a second growth forest landslide.

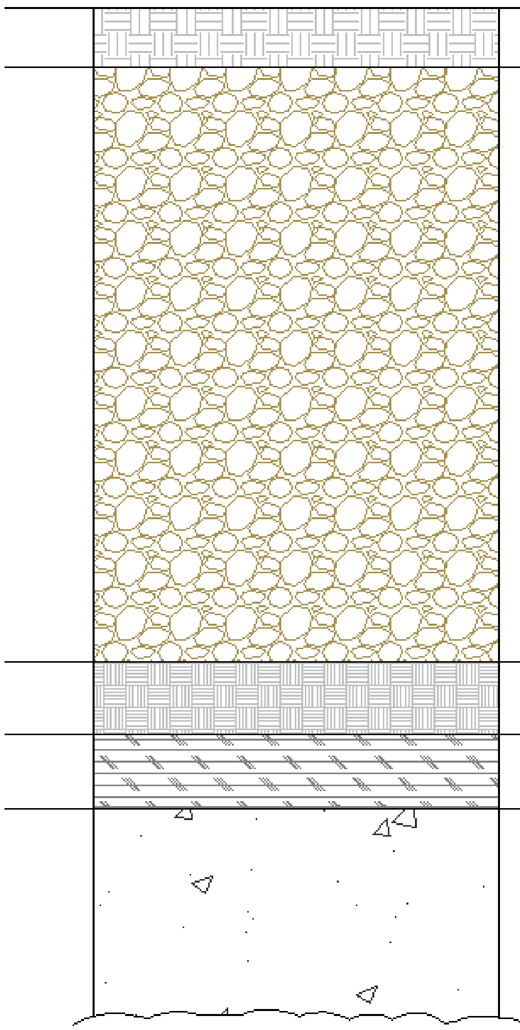



Figure 4.7: Typical section illustrating the location of the basal organic layer relative to inorganic soil layers and bedrock.

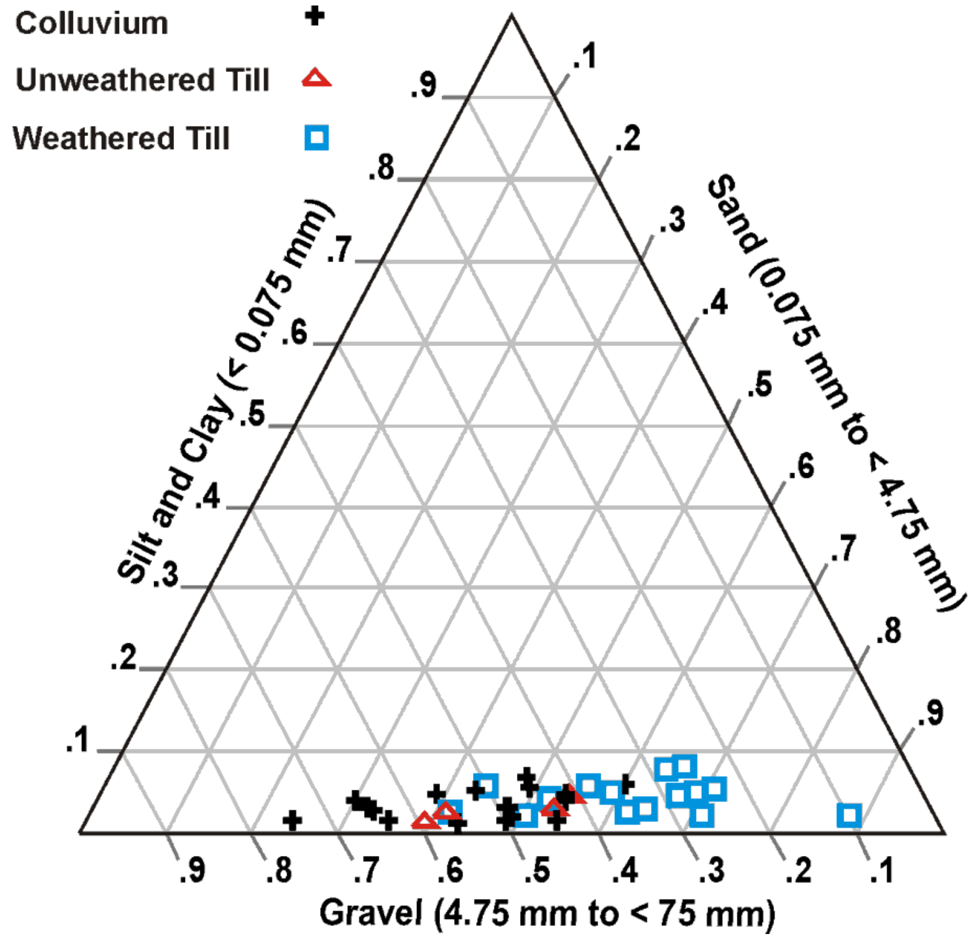



Figure 4.8: Ternary diagram showing particle size distribution for colluvium, unweathered till and weathered till observed at 36 out of 48 landslide sites visited.

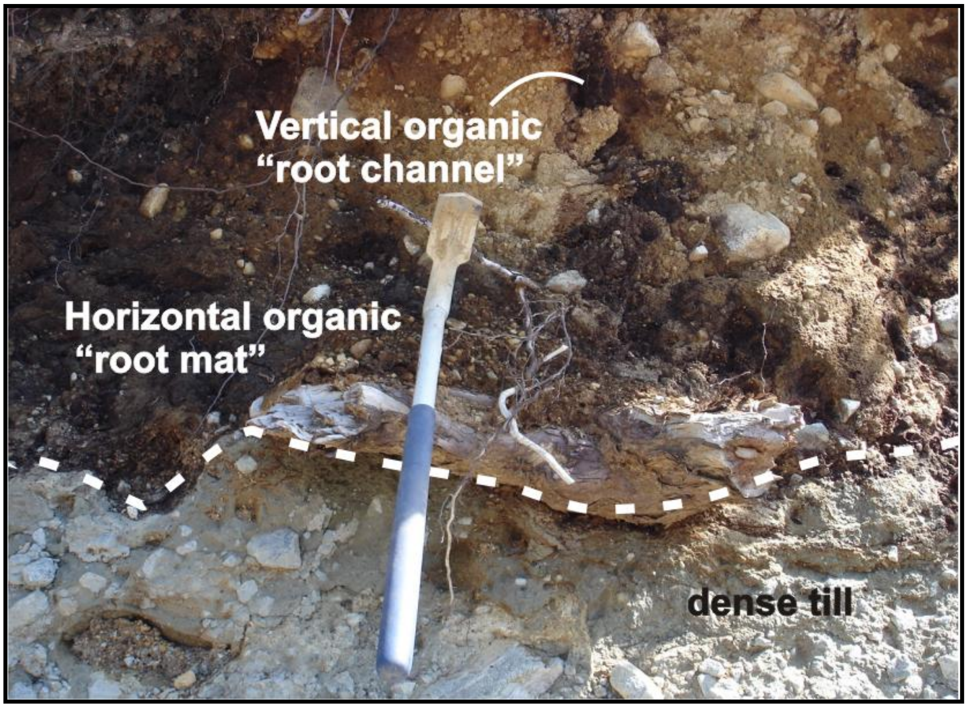



Figure 4.9: Organic layer developed along landslide failure slope and in root channels of the landslide headscarp.

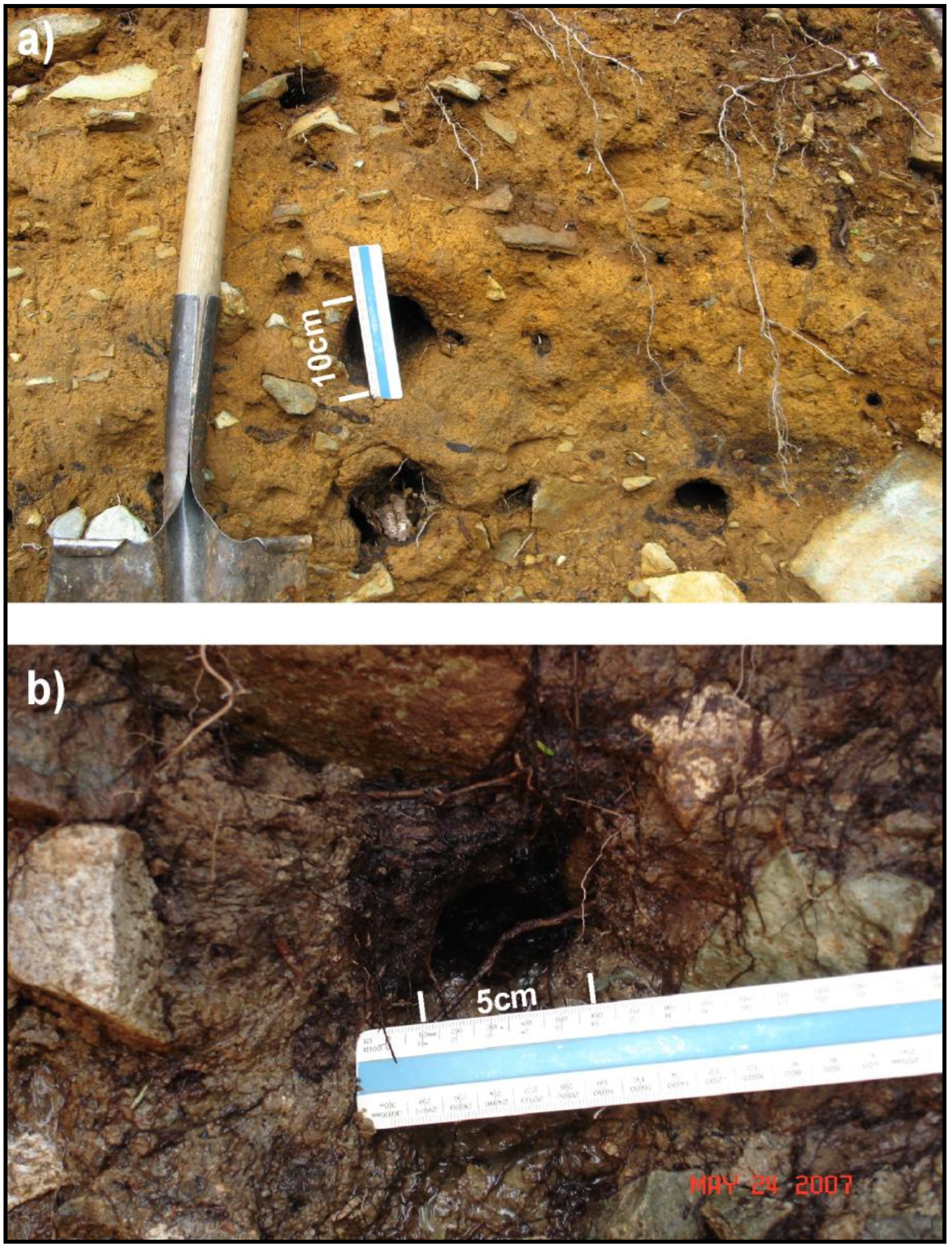



Figure 4.10: Macropores a) shows open root cavities remaining after decay of roots and free of organic deposits, b) shows root cavity infilled and partially plugged by organic layer deposits.

Figure 4.11: Organic layer infilling rock fractures along failure slope. Scale shows 1 cm increments.

Ten organic layer samples were analysed in the laboratory for moisture content and degree of humification. Seven samples were analysed for percent organic matter and particle size. The moisture content of the organic layer samples ranged between 90% and 530%. The average moisture content for the ten samples was 275%.

The soil colour ranged from yellowish brown (10YR 4/6) to black (10YR 2/1). One sample was light olive brown colour (2.5YR 5/3). Differences in colour were probably attributed to the parent soil and bedrock, degree of humification and percent organic matter (Hobbs, 1986; Nagle, 2000).

The soil ranged from moderate decomposition to complete decomposition according to the von Post classification for degree of humification (Table 4.1). The moderately decomposed samples consisted of recognizable plant structure and muddy water when squeezed. The completely decomposed samples were characterized by indiscernible plant structure with all organic material passing between the fingers when squeezed. The van Post classification was also used by Hobbs (1986) for the engineering classification of peats and Nagle (2000) for classifying Folisols.

Table 4.1: Degree of humification, von Post Classification, modified from Landva and Pheeney, 1980.

| **Degree of humification** | **Decomposition** | **Plant Structure** | **Content of amorphous material** | **Material extruded** | **Nature of residue** |
|---|---|---|---|---|---|
| $H_1$ | None | Easily identified | None | Clear, colourless water | |
| $H_2$ | Insignificant | Easily identified | None | Yellowish water | |
| $H_3$ | Very slight | Still identifiable | Slight | Brown, muddy water; no peat | Not pasty |
| $H_4$ | Slight | Not easily identified | Some | Dark brown, muddy water; no peat | Somewhat pasty |
| $H_5$ | Moderate | Recognizable, but vague | Considerable | Muddy water and some peat | Strongly pasty |
| $H_6$ | Moderately strong | Indistinct (more distinct after squeezing) | Considerable | About one third of peat squeezed out; water dark brown | |
| $H_7$ | Strong | Faintly recognizable | High | About one half of peat squeezed out; any water very dark brown | $H_6$ to $H_8$ Fibres and roots more resistant to decomposition |
| $H_8$ | Very strong | Very indistinct | High | About two thirds of peat squeezed out; also some pasty water | |
| $H_9$ | Nearly complete | Almost unrecognizable | | Nearly all the peat squeezed out as a fairly uniform paste | |
| $H_{10}$ | Complete | Not discernible | | All the peat passes between the fingers; no free water visible | |

The higher the degree of humification the lower the permeability of the organic layer (soil) (Hobbs, 1986). Nagle (2000) also found that the degree of humification affects the bulk density and therefore the permeability. Consequently, the lower the permeability, the fewer air voids for groundwater flow which results in higher pore water pressures during high rainfall events (Buchanan and Savigny, 1990).

Loss on ignition (LOI) testing and hydrogen peroxide ($H_2O_2$) were conducted to determine the percent organic matter for seven samples (Table 4.2). The mean percent organic matter by weight was 27% and 33% for $H_2O_2$ and LOI, respectively. The high percent of organic matter are also shown in the dry density of the organic layer. The unit weight of three organic samples was determined during direct shear testing. The unit weight of the organic layer samples was between 1.5 and 3.9 $kN/m^3$ indicating a relatively high organic content (Hobbs, 1986).

Table 4.2: Percent organic matter with respect to loss on ignition and hydrogen peroxide testing methods.

| **Test** | **n** | **Mean % Organic Matter (OM)** | **Minimum % OM** | **Maximum % OM** |
|---|---|---|---|---|
| Loss on Ignition | 7 | 33 | 12 | 58 |
| Hydrogen Peroxide | 7 | 27 | 8 | 52 |

Atterberg limits were completed for eight organic layer samples and compared to some British peats from an unrelated study (Figure 4.12). Atterburg limits were required to classify the organic layer according to the British Soil Classification System (BSCS). Oven and non-oven dried liquid limits were completed for the (organic layer) soil. After oven drying the plasticity of the organic layer was completely destroyed. Liquid limits also decreased to approximately 30% of the natural non-oven dried liquid limit values. Oven drying destroyed the organic layer plasticity and greatly modified the liquid limit of the organic layer. The non-oven dried organic layer samples plot below the A-Line and are greater than a liquid limit of 50. The organic layer should be classified, according to the BSCS, as ME, silt soil of extremely high plasticity due to the samples high liquid limit and location below the A-line. The high organic content of the sample classifies it as a Pt although the inorganic fraction of the soil is dominated by sand.

Soils plotting as ME are highly compressible due to the high organic content and liquid limit. These soils also have a high water holding capacity depending on the degree of humification. The higher the degree of humification the lower the porosity and moisture content (Hobbs, 1986; MacFarlane, 1969).

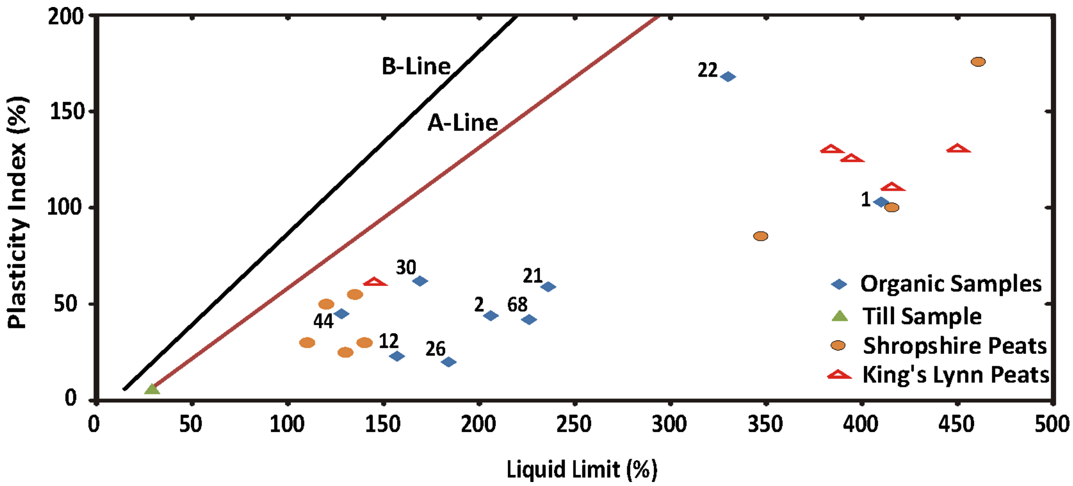



Figure 4.12: Atterburg Limits for organic layer samples (non-oven dried) from nine landslides for current study and some British peats from Hobbs (1986). Note: Organic Samples and Till Sample from current study.

A particle size analysis was also conducted for seven landslides on the inorganic soil portion of the organic layer after the organic matter was burned off using loss on ignition or hydrogen peroxide. The particle size distribution for particles less than 2 mm diameter was completed using the Mastersizer 2000. The particle sizes greater than 2 mm were combined with the results of the Mastersizer 200 analysis to determine the particle size distribution of the inorganic portion of the organic layer (Figure 4.13). The results show that the inorganic portion of the organic layer is between 56% and 87% sand size, 16% and 50% silt size, and less than 2% clay size (Table 4.3). The percent clay size for the organic layer is similar to many peats as shown by Hobbs (1986). The clay size is probably not a factor in the permeability of the organic layer since it comprises < 2% of the inorganic portion of the soil.

X-ray diffraction (XRD) was conducted on three samples (LS 2, LS12, LS22) to identify the clay minerals that are present in the organic layer. The samples were treated with hydrogen peroxide to remove the organic matter prior to the XRD analysis. The XRD analysis identified two clay minerals; Vermiculite and Palygorskite (Moore and Reynolds, 1989). Palygorskite was only identified in one sample, LS 2. The XRD analysis is only a qualitative method and does not determine quantities of any clay minerals.

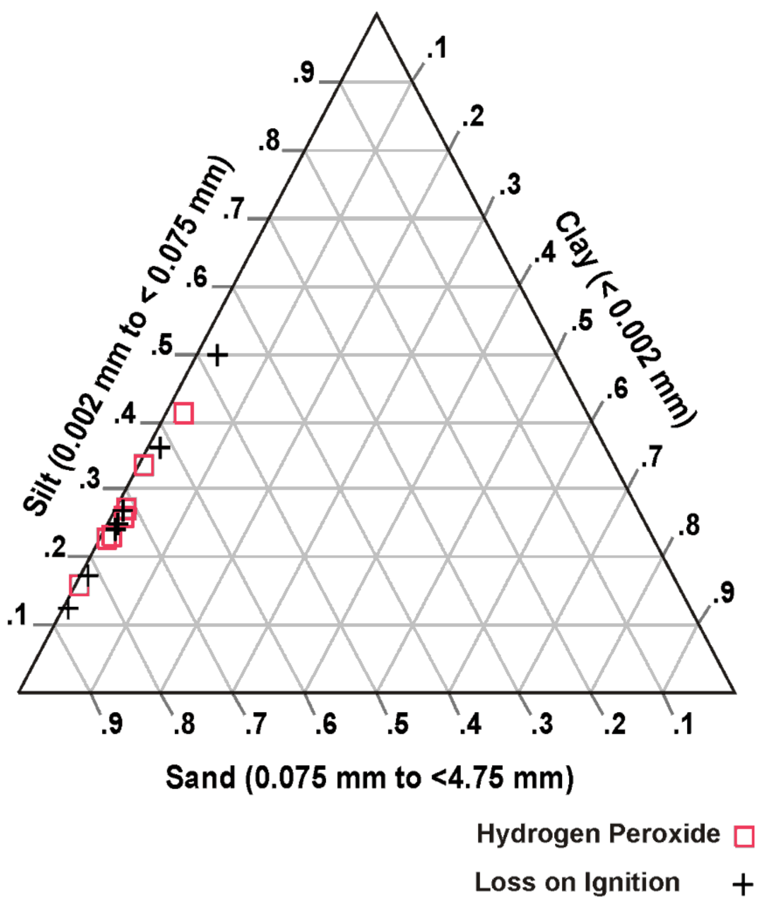



Figure 4.13: Particle size analysis for inorganic portion of the organic layer after organic matter was burned off using loss on ignition and hydrogen peroxide tests. Ternary diagram shows tests conducted on seven organic samples.

Table 4.3: Percent sand, silt, and clay size particles for seven samples using manual dry sieve and Mastersizer 2000 analysis after loss on ignition and hydrogen peroxide tests were conducted.

| | Hydrogen Peroxide | | | Loss on Ignition | | |
|---|---|---|---|---|---|---|
| Landslide # | % Sand | % Silt | % Clay | % Sand | % Silt | % Clay |
| 1a | 72 | 27 | 1 | 87 | 13 | < 1 |
| 1b | 76 | 23 | < 1 | 75 | 24 | 1 |
| 2 | 83 | 16 | < 1 | 82 | 17 | 1 |
| 12 | 66 | 33 | < 1 | 63 | 36 | 1 |
| 22 | 72 | 26 | 2 | 74 | 25 | 1 |
| 26 | 56 | 41 | 3 | 72 | 27 | 1 |
| 44 | 76 | 23 | 1 | 48 | 50 | 1 |

Direct Shear tests were conducted on three organic layer samples in the geotechnical laboratory at the British Columbia Institute of Technology. The Direct Shear tests were completed under consolidated undrained conditions at a shear rate of 0.25 mm/min.  The relatively small horizontal shear displacement rate is designed to minimize excess pore water pressures during testing (Bowles, 1992). The angle of friction values were between 33° and 38.4° for the organic layer samples (Figure 4.14).  Cohesion values ranged between 1.1 and 3.6 kPa. The results of the Direct Shear tests show that the material has friction angles comparable to a cohesionless soil. The cohesionless nature of the soil could be due to the predominantly sand fraction within the organic layer. The sand and to a lesser extent gravel could be responsible for the higher friction angle.

The results from this study are similar to Nagle (2000) where an average angle of friction for nine samples was determined to be 41°. These results were for a Folisol on the north coast of BC. The angle of friction from that study was calculated from the Folic soil – bedrock interface. In comparison, several studies have also been conducted on inorganic forest mineral soils, eg. colluvium and till, in the Pacific Northwest. Schroeder et al. (1983) determined a cohesive silty sand to have an average angle of friction of 35.5° on the Washington and Oregon Coast. Another study conducted in North Vancouver by O'Loughlin (1972) determined that a gravelly sand loam over compact till with no roots had an angle of friction between 34° and 41°. Comparing the current study and Nagle (2000) to the inorganic soil studies, it appears that the difference in angle of friction is not a determining factor in landslide initiation. To conclude that the angle of friction is a determining factor there should be a larger difference between the angle of friction for organic soils/layers and inorganic soils. The results do not show a large difference in angle of friction. MacFarlane (1969) stated that the shear strength of peat is not a limiting factor for geotechnical design and that deformation characteristics may be more important. The cohesion values are very low, although this analysis does show that there is some cohesion in the organic layer.

Another factor in the unexpectedly high friction angle could be due to the lab testing procedure compared to the in-situ state of the organic layer. Prior to Direct Shear testing the samples were reworked, remoulded and preconsolidated therefore, breaking down the natural open structure of the organic layer samples. Reworking and compacting the soil would result in a higher soil shear strength leading to a higher friction angle than the in-situ undisturbed state.

In addition, the Direct Shear tests only considered the shear strength of the organic layer. Direct Shear tests did not consider a combination of the underlying bedrock or dense till with the organic layer. The angle of friction between the organic layer and an underlying dense till or bedrock should be lower. This combination of organic layer with a higher strength underlying material should be researched to determine its effects on friction angle.

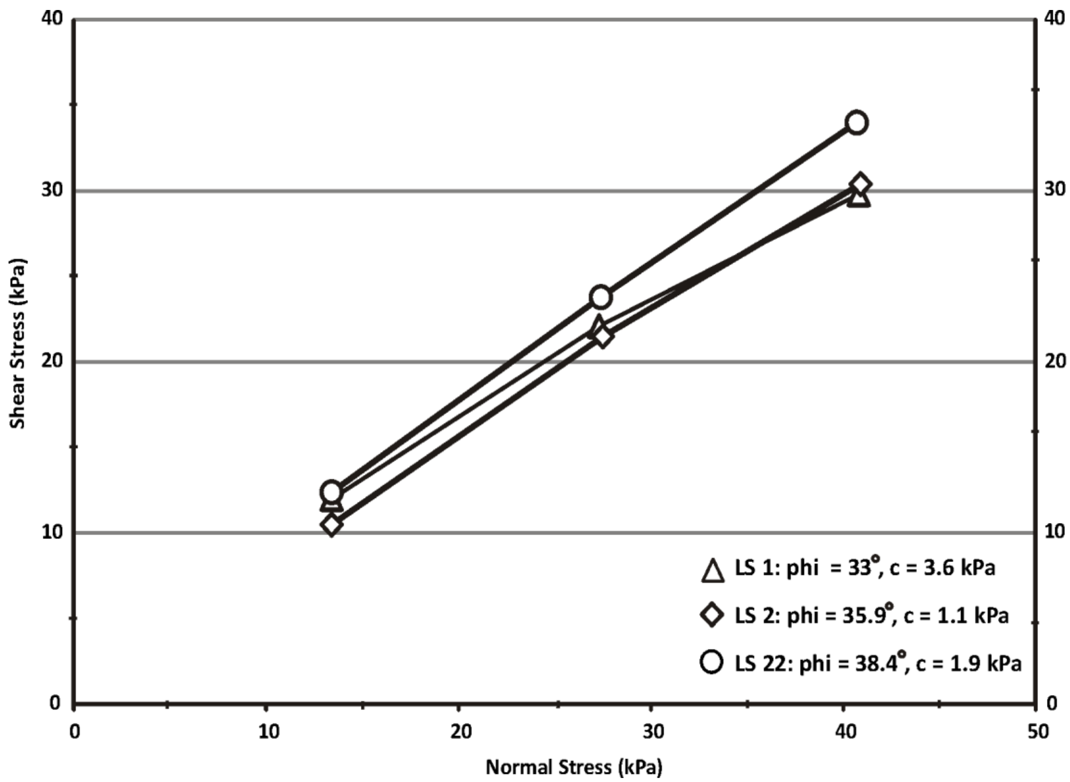



Figure 4.14: Direct shear tests conducted on three organic layer samples. Friction angles range between 33 and 38 degrees, and cohesion between 1.1 and 3.6 kPa.

### 4.4.2 Statistical Analysis

A comparison between terrain attributes and the presence of organic layer was conducted for 48 open slope landslides. Wilcoxon tests showed that there was a significant difference (p=0.05) between the median failure slope (the measured slope of the failure surface in the initiation zone) angle for organic layer (present) and non-organic layer (absent) at 34˚ and 39˚, respectively (Table 4.4).

There is a significant difference (p= 0.01) in soil depth with a median depth of 1.0 m and 0.5 m for organic layer and non-organic layer, respectively. There is a significant difference (p= 0.05) in landslide area with a median total area of 5600 $m^2$ and 2700$m^2$ for organic layer and non-organic layer landslides, respectively. Another significant difference ($p= 0.05$) was detected for landslide length with a median length of 276 m and 133 m for organic layer and non-organic layer associated landslides, respectively. Although not significant, organic related landslide initiation zone volume was generally greater than non-organic layer.

Chi-Square or contingency tests were conducted to test significant differences between landslide attributes for organic layer (present) and non-organic layer (absent) associated landslides (Table 4.5) and indicate terrain attributes that were characteristic for organic layer and non-organic layer. Organic layer associated landslides are more likely to occur on concave, mid-slopes to upper slope positions with poorly to imperfectly drained morainal soils between 0.5 and 1.5 m thick whereas non-organic layer landslides are more likely to occur on lower to middle slope positions with well drained colluvial soils less than 0.5 m thick (Figure 4.15 a, b and c; Figure 4.16 a, b, c and d). Organic layer landslides are also more likely to occur on slopes between 25˚ and 40˚ whereas non-organic layer landslides are more likely to occur on slopes between 35˚ and 45˚ (Figure 4.15 a). This is in contrast to the direct shear tests which indicated an angle of friction between 34° and 39°. This indicates the importance of high pore water pressures due to the low permeability organic layer and therefore resulting in landslides on slopes less than the angle of friction.

Organic landslides also occur where bedrock is exposed within 10 m of the initiation zone. The presence of exposed bedrock could be related to reduced permeability, therefore creating ideal conditions for the accumulation of the organic layer deposits. There is also an increase in organic layer presence with elevation. It is unclear why this is occurring but one hypothesis is that with increased elevation there is also increased precipitation and ideal wet condition for accumulation of the organic layer. In addition, cooler temperatures with increased elevation could be affecting decomposition by allowing the organic layer to accumulate more at higher elevations.

Non-organic associated landslides are more likely to occur on convex and straight slopes on lower and mid-slope positions with moderately well to well drained colluvial soils less than 0.5 m thick than organic layer landslides (Figure 4.15 a, b, and c; Figure 4.16 a, b, c, and d).

Table 4.4: T-tests for organic layer presence vs. terrrain attributes. (n = 48)

| **Dependent Variable** | **P-value Wilcoxon** | **Median Value** | |
|---|---|---|---|
| | | Present | Absent |
| Failure Slope (˚) | 0.029 | 34.0 | 39.0 |
| Origin Slope (˚) | ns | 36.0 | 39.0 |
| Soil Depth (m) | 0.004 | 1.0 | 0.5 |
| Rooting Depth (m) | ns | 0.3 | 0.3 |
| Root Density (Roots/$m^2$) | ns | 129 | 111 |
| Elevation (m) | ns | 465 | 507 |
| Initiation Zone Width (m) | ns | 17 | 15 |
| Initiation Zone Length (m) | ns | 21 | 20 |
| Initiation Area ($m^2$) | ns | 340 | 368 |
| Initiation Volume ($m^3$) | ns | 388 | 221 |
| Total Landslide Area ($m^2$) | 0.025 | 5600 | 2700 |
| Landslide Length (m) | 0.029 | 276 | 133 |

Table 4.5: Chi Square test for terrain attributes vs. presence of organic layer. (n = 48)

| | P-value | |
|---|---|---|
| **Dependent Variable** | **Pearson** | **Fisher's** |
| Failure Slope Class (˚) | ns | |
| Soil Depth Class (m) | 0.004 | |
| Elevation Range (m) | 0.024 | |
| Exposed Bedrock | 0.006 | 0.005 |
| General Drainage Class | 0.020 | 0.020 |
| Seepage | ns | |
| General Soil Type | 0.009 | |
| Vertical Curvature | 0.0002 | |
| Horizontal Curvature | ns | |
| Slope Position | ns | |
| Macropores Evident | ns | ns |

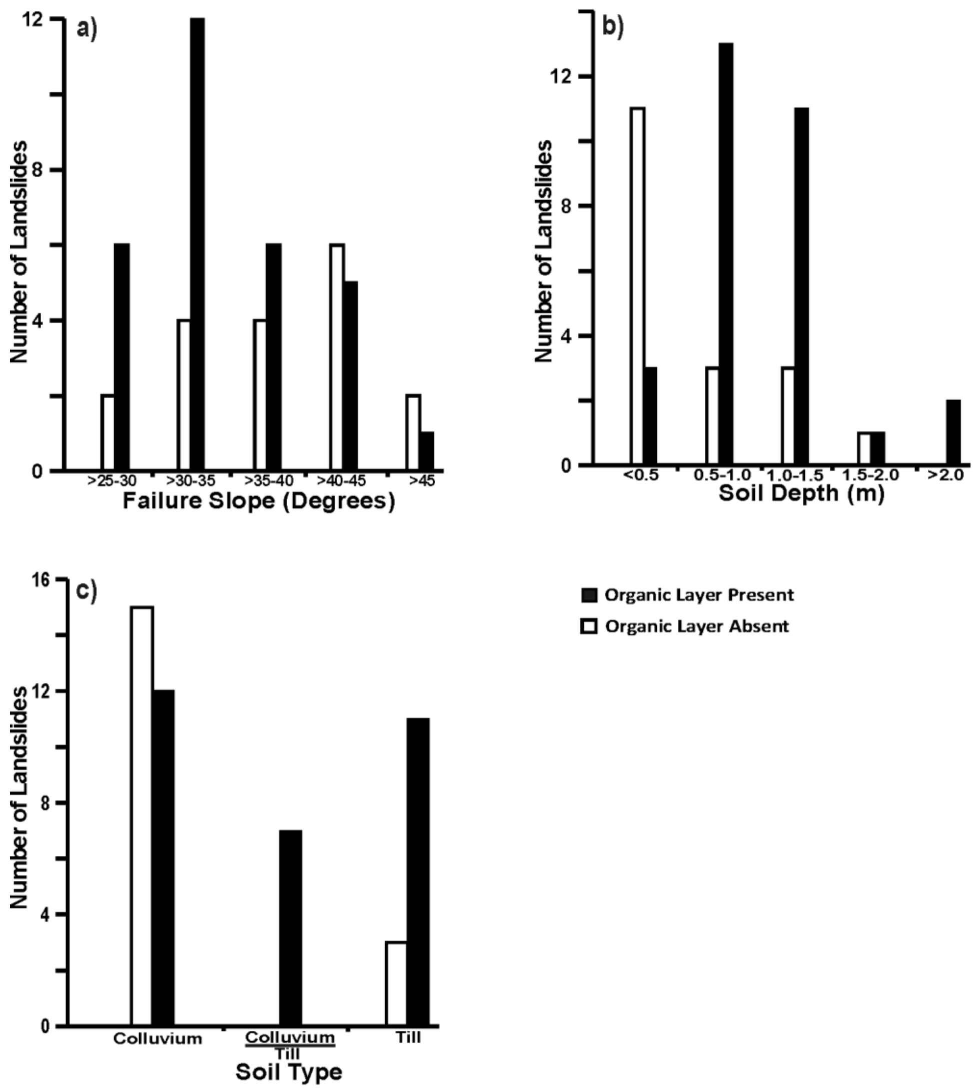



Figure 4.15: Histograms for terrain attributes: a) initiation failure slope, b) soil depth, c) soil type.

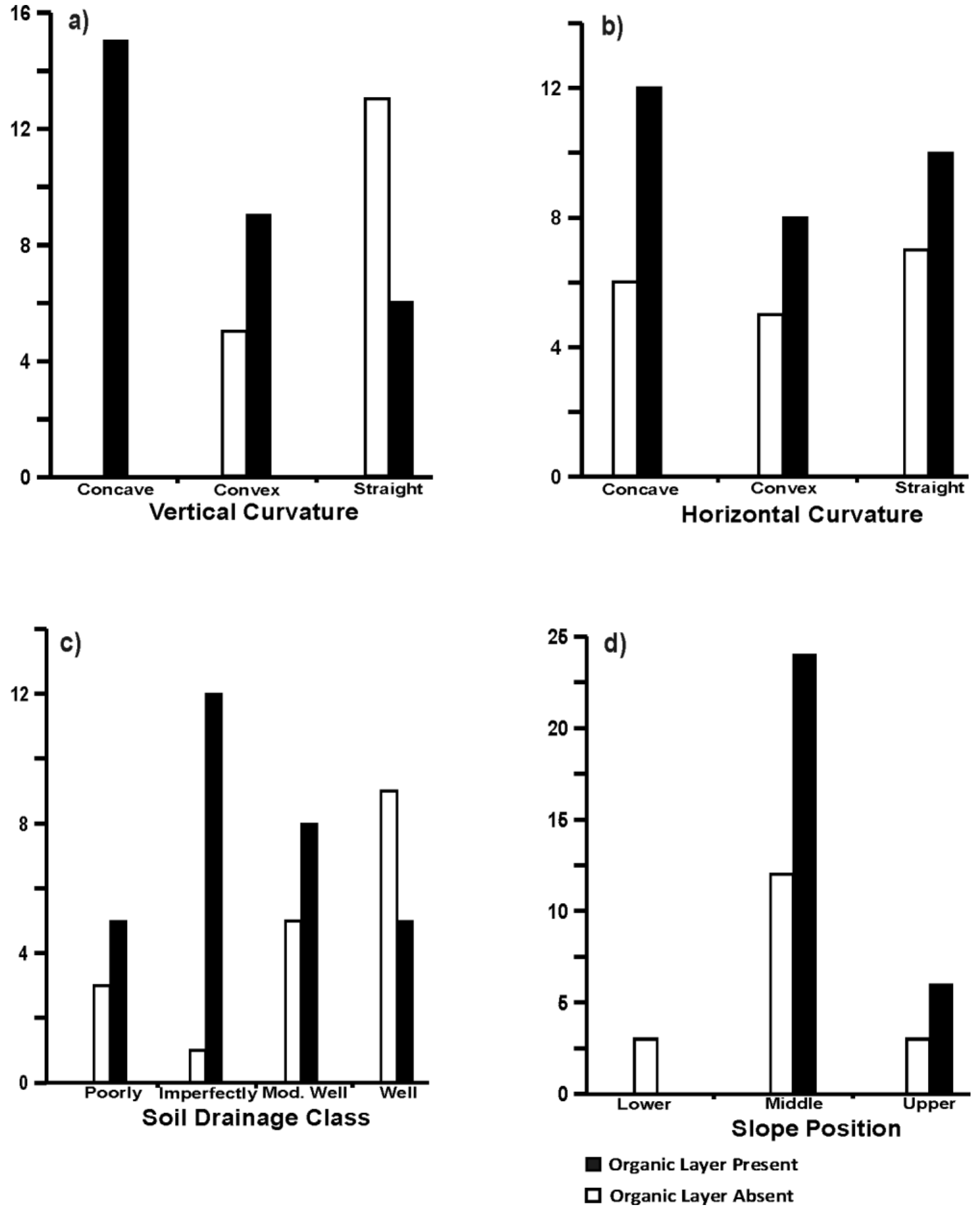



Figure 4.16: Histograms for terrain attributes: a) vertical slope curvature, b) horizontal slope curvature, c) soil drainage class, d) slope position.

The field data collection of landslide attributes has allowed a detailed analysis of the important variables involved in slope failures for organic layer deposits. The null hypothesis is that organic layer and non-organic layer related landslides occur on similar terrain with no significant differences. However, this research indicates a significant difference between slope gradient, slope shape, soil drainage, soil type and soil thickness. Thus, the alternative hypothesis holds true that organic and non-organic layer landslides initiate on different terrain. These differences in terrain attributes may result from the fact that organic layer landslides only require gentle slopes to initiate since the organic layer is reducing the factor of safety of the slope by reducing permeability and increasing pore water pressures. Site factors such as dense low permeability morainal (till) soils and bedrock could also be inhibiting soil drainage and creating the ideal conditions for the accumulation of the organic layer.

## 4.5 Conclusions

The organic layer deposits are generally moderately to completely humified causing the permeability of the layer to decrease. Moisture content is very high due to the high organic content of the deposit. Consequently, permeability of the organic layer is probably a major factor in reducing slope stability depending on the degree of humification. Based on three tests conducted on the organic layer, the angle of friction does not appear to be a determining factor since it is similar to tests conducted by previous studies for inorganic soil (till and colluvium) on forested slopes. However, remoulding of the organic layer samples during direct shear tests may have resulted in a higher shear strength than the in-situ organic layer.

Organic layer landslides occur on significantly different terrain from non-organic landslides. The terrain attributes where organic layer landslides occur is more prone to wet site conditions due to poor site drainage, and possibly to higher elevations where higher precipitation and cooler temperatures prevail.

The organic layer appears to be derived from the decay of roots as observed by previous studies (Sanborn and Lavkulich, 1989 a). Organic layer deposit were observed plugging macropores in the headscarps of several landslides. Plugging of macropores and reduced permeability leading to increased pore water pressures is probably a contributing factor in some of the landslides.

# 5: Conclusions and Future Research

The November 15, 2006 storm event on southwestern Vancouver Island was an excellent opportunity to collect and study data from a large number of landslides within a relatively small geographic area. In order to carry out a landslide study, an MSc project was developed in cooperation with the British Columbia Forest Service and Simon Fraser University. Objectives for this study included:

- how accurate is change detection at identifying landslides and windthrow;
- how does windthrow impact slope stability;
- how does the landslide density and magnitude differ from other studies;
- how does root reinforcement change after harvesting; and
- what are the geotechnical properties of an organic layer observed at several landslide locations.

## 5.1 Effects of Windthrow

A landslide and windthrow inventory was completed, identifying 233 landslides and 404 windthrow patches in the project area. The inventory involved the use of change detection, post storm high resolution ortho-photo imagery and field reconnaissance. The high resolution ortho-photo imagery and field truthing identified more landslides and windthrow than a previous automated change detection study by the MOE, which only used the lower resolution SPOT satellite imagery (Guthrie et al., 2010).

This windthrow analysis identified areas most susceptible to windthrow and windthrow landslides on a site and landscape level. A statistical analysis of the field data showed a significant difference between windthrow and clearcut terrain attributes. Windthrow associated landslides are more likely to occur on steeper, convex and straight slopes on lower and upper slope positions with well drained, thin, colluvial soils whereas clearcut landslides are more likely to occur on gentler, concave slopes on middle slopes with poorly drained thicker, morainal soils. These terrain attributes for windthrow landslides are also indicative of poor growing conditions and inoperable terrain surrounding some clearcuts.

The GIS analysis indicates that windthrow and windthrow related landslides develop in clusters across the landscape. The clusters of landslides are characterized by several attributes such as steep slopes, old growth forest, clearcut edges and topographic exposure. Clearcut adjacency is a major factor in the location of windthrow landslides. A majority of windthrow associated landslides occur within 70 m of a clearcut boundary and most of the clearcuts are <10 years old. The impacts of forest openings and the age of the openings is a major factor in the location of the clusters.

Windthrow landslide distribution also tends to be influenced by forest type. All the windthrow landslides occurred in old growth forests and none were observed in second growth stands.

Finally, the clusters are also influenced by valley orientation and orography. Most of the clusters are located at valley junctions, on steep terrain, on south to southeast aspects. The storm fronts are probably impacting these areas as they progress up the river valleys from the coast with wind driven rain and intense precipitation storm cells. The windthrow slope aspects also correspond with the predominant surface wind direction during the storm event.

Several causes of slope failure were observed during our field data collection at the windthrow landslide sites. Loss of forest canopy and the exposure of mineral soil likely caused saturation of the soil during the storm event contributing to slope failure. The loss of root strength is another factor in the initiation of the windthrow landslides since the roots were pulled out of the soil at most of the windthrow landslide sites. Disturbed drainage due to the uprooting of the trees was also observed at five sites and is another mechanism that concentrates surface flows reducing slope stability.

The results of the landslide density analysis determined that the windthrow landslide density is 6.15 landslides/km$^2$ and the clearcut (≤15 years) landslide density is 0.25 landslides/ km$^2$. The landslide density for windthrow was 25 times the 'clearcut' density and 123 times the 'natural' density. It could be argued that the windthrow landslides are logging related since they occur adjacent to clearcuts and are directly influenced by clearcut location and age. The combination of clearcut (≤15 years) and windthrow landslide density is 0.54 landslides/ km$^2$. The clearcut landslide density is comparable to other studies but the windthrow is difficult to compare since there are no known previous studies on windthrow landslide density.

## 5.2 Root Reinforcement

A root density analysis was completed for 28 landslides. The 1 to 10 mm diameter roots are the most sensitive to decay after logging and there is an exponential loss of root density in the first 11 years. Our results show a 70 to 90% loss in root density during this time period. Root quality was also analysed showing a low point between 4 and 11 years. Second growth stands (>15 years old) show root densities that are nearly 2.5 times that of a new clearcut or an old growth windthrow stand. The number of root density samples was small in the second growth stands but there is evidence to show that older clearcuts have higher root densities than new clearcuts. More research is required with respect to second growth root densities to understand the growth and decay of roots in these stands.

The highest landslide density is between 4 and 11 years after timber harvesting. This high landslide density corresponds to the root density minima between 4 and 11 years after harvesting. The first 2 years after harvesting is responsible for 27% of the landslides. There was minimal root density loss within the first two years indicating that other factors are responsible for the landslides occurring during this time period. These factors are rapid decay of roots that were not detectable during the field data collection or hydrological conditions such as forest canopy removal, or crushing of macropores during logging, or disturbed surface drainage patterns.

The rooting characteristics of tree species also have a role to play in root reinforcement. Most roots were lateral roots indicating that the reinforcement is predominantly within the top 0.5 m of the soil profile. The roots are acting as a mat near the surface of the soil rather than using deeper roots to wedge or anchor into the lower soil horizons or bedrock. However, the data set is relatively small and more research is required to investigate the influence of tree species. The second growth stands with high root density were characterized by Douglas-fir and young healthy plantations whereas the lowest density stands in old growth and recent clearcuts were characterized by generally older unhealthy stands of balsam and hemlock.

## 5.3 Organic Layer

An analysis involving the terrain attributes and geotechnical properties was completed for an basal organic rich layer observed at approximately 60% of the landslide locations. The organic layer was identified as a relatively thin layer of well to completely humified organic matter probably derived from the accumulation of tree roots.

The direct shear tests were inconclusive since the resulting angles of friction were not different from other studies on inorganic forest soils. Reworking of the organic layer samples may have increased the shear strength of the organic samples during Direct Shear tests. The high percentage of organic matter allows the layer to have a very high moisture content depending on the degree of humification. The degree of humification was between moderate and completely humified which indicates that the organic layer has a low permeability. The low permeability of the organic layer is probably a determining factor in the stability of the slopes where these landslides occur. In addition, the organic layer was often located on low permeability soil layers or bedrock resulting in even poorer drainage.

A statistical analysis of the field data showed a significant difference between organic layer and non-organic layerl landslide terrain attributes. Organic layer landslides are more likely to occur on gentle, concave slopes on upper slope positions with poorly drained thick, morainal soils than non-organic layer landslides, which are more likely to occur on steeper, convex slopes on lower slopes with well drained thinner, colluvial soils.

## 5.4 Future Work

Future work on windthrow landslides could involve the use of the windthrow probability prediction model developed at the University of British Columbia by Dr. Steve Mitchell. Landslide locations identified in this study could be input into the windthrow probability model. The analysis could be completed by overlaying the landslides from this study to see if they overlap areas in the prediction model that are classed as high hazard windthrow polygons. The windthrow probability model has historic weather information in its database that could be used to better understand the effects of weather patterns on windthrow landslide initiation.

Future studies involving windthrow and landslides should use higher resolution satellite imagery in conjunction with increased field checking to reduce errors in the inventory. Although intensive field truthing is labour intensive if combined with high resolution satellite imagery, the two could be very useful in future windthrow landslide research projects.

Further analysis within the GIS database could be conducted to determine if any other correlations exist with respect to landslide distribution on a landscape level. Advanced techniques with multivariate statistics and GIS would be essential for the completion of this analysis.

The results from this research should be integrated into existing British Columbia forestry manuals for windthrow hazard. This would be an excellent opportunity to integrate the results from this study with existing windthrow manuals and hazard guidelines to reduce landslide hazards in forested terrain. This could result in fewer landslides along clearcut edges if forestry professionals are aware of the risk of windthrow landslides.

Future work in determining the effects of root reinforcement on slope stability should include a larger database of landslides. A larger database is required particularly in the second growth stands and old growth forests. This study collected data from eight landslides in second growth and five in old growth but more are required to have a complete analysis of the root density within these stands. Collection of the root density data would require the same techniques as the original field data collection including sampling from fresh landslides.

It would be ideal to understand the root density of trees within natural old growth stands that are not in windthrow areas.  The old growth windthrow trees could be affected by previous windstorms and may not be indicative of true old growth forests. A database similar to the second growth stands should be collected from new landslides on southern Vancouver Island as they occur.

Future research could also include root density information on deciduous trees and brush species. During the field data collection, a high number of brush roots were observed in some locations. Previous studies have analysed the role of brush and deciduous trees and their role in slope stability.

The role of tree species on root density is another aspect of the project not researched in detail. More information on tree species and their corresponding root density and quality would be useful information for a complete root database.

The hydraulic conductivity of the organic layer is another property that could be further examined. Falling head tests could be conducted to determine the soils hydraulic conductivity.

Further testing could be conducted on the shear strength of the organic layer material using a triaxial test. The triaxial test is conducted on the sample by regulating pore pressure. The test should be conducted on undisturbed samples. Organic samples should be taken from landslide scarps, ensuring preservation of original shape and soil structure. Preservation of samples could be accomplished by cutting the samples with a knife and placing in a water tight container or wax mould.

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# Appendices on CD-ROM

## Appendix A: Windthrow Data

Statistical tests in MS Word (.doc)

## Appendix B: Root Data

Statistical tests in MS Word (.doc)

## Appendix C: Organic Layer Data

Statistical tests in MS Word (.doc)
Direct shear test analysis in RocLab (.emf)
Direct shear tests and consolidation in Excel spreadsheets (.xls)
Grain size analysis in Excel spreadsheets (.xls)
Atterburg limits in Excel spreadsheets (.xls)
Mastersizer grain size analysis in Excel spreadsheets (.xls)
X-ray diffraction analysis in MS Word (.doc)

## Appendix D: Field Data

Field data in Excel spreadsheets (.xls)

## Appendix E: GIS Data

GIS data in Excel spreadsheets (.xls)
GIS shape files (.shp)

The CD-ROM, attached, forms a part of this work.