Mountain Slope Stability and Land Use
Telkwa mudflow
Forestry operations in British Columbia occur across large tracts of land, often with terrain subject to post-loggin landslides broadly distributed throughout the landscape.
The extent to which logging contributes to landslides has been determined for Vancouver Island. The results are highly variable and range from a trebling to more than an order of magnitude. They illustrate the difficulty of applying knowledge of frequency changes in a particular area to the broader region.
Logging roads in a watershed block and re-route water, overload, undercut and saturate slopes, and generally have the greatest impact in terms of landslide occurrence.
Harvesting may result in increased landslide frequency due to changes in the hydrology of slopes and in reducing shallow slope strength by the eventual loss of anchoring root systems through rot.

Cumulative landslides in Nahwitti River watershed, Vancouver Island, show a 16-fold increase in frequency of landslides following logging.
On Saturday, Aug. 07, 2004, two large mud slides crashed down a mountain in southeastern British Columbia, Canada. The larger of the two Creston, BC mud slides was up to four metres deep and 90 metres wide in places. Together, the slides destroyed a number of cars, a garage, and at least three houses, but there were no casualties or reported injuries.

The mud slides were probably caused by recent heavy rain in combination with bush fires earlier that year. The bush fires cleared the mountain of trees, meaning that no roots held the soil and therefore leaving the area in threat of mud slides.
Role of Forest Vegetation in the Stability and Protection of Alpine Slopes
A well developed vegetation cover influences the intensity of hillslope processes in variety of ways, not only through indirectly controlling the size of the surface forces, but also through adding to the shear strength of the soil mantle.

Two components of the vegetation cover need to be consider:

- the effects on soil erosion.
- the effects on mass movements
Grasses and forbs, and to a lesser extent woody vegetation, prevent surficial erosion on mountain slopes by processes of:

1) **Interception**: foliage and plant residues absorb rainfall energy and prevent soil compaction from raindrops.

Plant canopies intercept the energy of raindrops, thereby minimizing their impact on the soil surface. For this reason, runoff and erosion potentials on disturbed lands are highest during periods when no plant canopy is present and the soil is directly exposed to raindrop impact. Once a full canopy is established, the potential for runoff is greatly reduced.
2) Restraint: root system physically binds or restrains soil particles while above-ground residues filter sediment out of runoff
3) **Retardation**: above-ground residues increase surface roughness and slow velocity of runoff.

4) **Infiltration**: roots and plant residues help maintain soil porosity and permeability.
5) **Transpiration**: depletion of soil moisture by plants delays onset of saturation and runoff.

Transpiration is the loss of water from plant leaves. Water exits the leaf through stomata, which are tiny pore spaces in the leaf. The rate of transpiration depends on air temperature and solar radiation.
Prevention of Mass-Movement

Vegetation, primarily woody plants, helps to prevent mass-movement, particularly shallow sliding in slopes. Possible ways woody vegetation might affect the balance of forces in a slope include:

1) **Root reinforcement**: roots mechanical reinforce a soil by transfer of shear stress in the soil to tensile resistance in the roots.

2) **Soil moisture modification**: evapotranspiration and interception in the foliage limit buildup of soil moisture stress. Vegetation also affects rate of snowmelt, which in turn affects soil moisture regime.

3) **Buttressing and arching**: anchored and embedded stems can act as buttress piles or arch abutments in a slope, counteracting shear stresses.

4) **Surcharge**: weight of vegetation on a slope exerts both a downslope (destabilizing) stress and a stress component perpendicular to the slope which tends to increase resistance to sliding.

5) **Root wedging**: alleged tendency of roots to invade cracks, fissures, and channels in a soil or rock mass and thereby cause local instability by wedging or prying action.

6) **Windthrowing**: destabilizing influence from turning moments exerted on a slope as a result of strong winds blowing downslope through trees.
1) Root reinforcement
2) Soil moisture modification
3) Buttressing and arching
4) Surcharge
5) Root wedging
6) Windthrowing

• the first three effect or influences (root reinforcement, soil moisture depletion and buttressing) enhance slope stability.

• the fourth, surcharge, may have either a beneficial or adverse impact depending on soil or slope conditions.

• the last two, wind throwing and root wedging, on the other hand, are likely to affect slope stability adversely. Strong winds blowing parallel to the ground surface will exert an overturning movement on trees. This can lead to so called wind throwing or blowdowns which result in localized disturbances in the soil mantle.
The most obvious way in which woody vegetation stabilizes slopes is by root reinforcement. The intermingle roots of plants tend to bind the soil together in a monolithilic mass. On slopes, the vertical root system (ie. the main taproot and secondary sinker roots) can penetrate through the soil mantle into strata below (eg. fractured or disintegrated bedrock), thus anchoring the soil to the slope and increasing resistance to sliding.
It is important to appreciate that the significance of mechanical stabilisation of slopes by tree roots depends primarily on the depth of the potential slip surfaces, the likely failure mode and the steepness of the slope. A general classification scheme for forested soil slopes involves four conditions:

1. shallow soil overlying homogeneous bedrock
2. shallow soil covering fractured bedrock
3. thick soil cover with a transition zone
4. thick soil mantling potentially deep failure surfaces.
The root system of a tree performs many vital functions:

- Roots store food needed to produce spring foliage, absorb and transport water and minerals from the soil, and anchor the tree to the ground.

- Root systems actually consist of larger perennial roots and smaller, short-lived, feeder roots.

- Large, woody tree roots and their primary branches increase in size and grow horizontally. The small feeder roots constitute the major portion of the root system's surface area.

- Feeder roots grow out from large woody roots and usually grow up toward the soil surface.

- The major function of feeder roots is the absorption of water and minerals. Feeder roots are located throughout the entire area under the canopy of a tree. As much as 50 percent of the root system grows beyond the drip line and may extend as far as the height of the tree.
The species with the greatest volume of roots were those for which the greatest root lengths measured.

Although the root volume distribution gives an indication of the total cross-sectional area of root at a specific depth, it does not reflect the root length distribution and hence the pull out strength for the same root volume can represent different root lengths and diameters.
Root length distribution with depth

- Generalised volumetric root distributions indicate the maximum volume is found at a common depth for all the species.
- Species with the greatest root lengths are those which demonstrate the greatest pull out resistance.
When a tree root extends across a shear surface and perpendicular to it or upwards beyond the potential failure mass making a small angle with the downslope direction of the shear zone, the root within the shear zone develops tension.

**LEGEND**

- $z$: Thickness of shear zone
- $x$: Horizontal deflection of root
- $\theta$: Angle of shear distortion
- $T_R$: Root tensile strength
- $\tau$: Skin friction along root
• A root- or fiber-reinforced soil behaves as a composite material in which elastic fibers of relatively high tensile strength are embedded in a matrix of relatively plastic soil.

• Additional strength is mobilized within the composite material by the development of tractive forces between the particles and the surrounding matrix.

• In other words, shear stresses in the soil mobilize tensile resistance in the fibre, which in turn imparts greater strength to the soil.

The net effect of fiber reinforcement on the stress-strain response of soils is to increase the shear strength of the soil. Another important effect is to make some soils tougher, that is able to resist continued deformation without loss of residual strength.

A – without fibre
B – with fibre

Stress-strain response under shear

Shear Stress
Shear strain

A
B
The main effect is to displace the shear or failure envelope upward, thus providing additional cohesion. This behaviour is demonstrated in the results of direct shear tests on dry dune sand reinforced with different lengths of a natural fiber. The test results show that a threshold or critical confining stress must be equal or exceeded in order to mobilize the maximum contribution from fiber reinforcement. In this particular case the critical confining stress is a function of fiber length.
In the case of direct shearing of soil masses permeated by roots, most of the roots will develop tension. At the time of failure, roots within the failure zone may break due to tension, be sheared, or be pulled out. Where the roots extend below the shear surface they are likely to be finer and hence may also be broken or pulled out.
Root morphology and strength

- The pull out resistance of a tree is generally controlled by its root strength and morphological characteristics.
- Trees roots usually consist of both a lateral root system and a central vertical root system.
- Secondary vertical or near-vertical roots called sinkers may grow down from the laterals.
- Although the lateral roots play a role in binding the soil on a slope together, the main resistance to sliding on hillslopes is provided by the vertical roots.

Some tree species are predisposed by heredity toward development of deep central taproots; others are not.
The volumetric root distribution does not always reflect the true pull out strength of a species as the same root volume can represent different root lengths and diameters.

For a given root volume, longer roots of smaller diameter are likely to result in a greater root tensile strength and hence an increased pull out resistance.

Relationship between root tensile strength and root diameter

Relationship between root tensile resistance and root diameter
1. Root reinforcement

2. **Soil moisture modification**

3. Buttressing and arching
4. Surcharge
5. Root wedging
6. Windthrowing

Trees can increase slope stability by intercepting rainfall that would otherwise have infiltrated, and by extracting soil moisture for transpiration. Both processes enhance shear strength by reducing positive pore-water pressure and encouraging the development of matric suction.
Canopy interception and stemflow tends to concentrate rainfall locally around the stem of plants, creating higher local pore-water pressures, while root development and associated biological activity creates macropores that increase infiltration capacity and concentrate flow deeper into the bank.

These effects are most pronounced during and immediately after large rainfall events of the type that are often associated with slope failure.

Roots often grow outward to a diameter one to two times the height of the trees.
Vegetation can affect the stability of slopes by modifying the hydrologic regime of the soil. Trees transpire water through their leaves and this in turn depletes soil moisture. A forest can also intercept and adsorb moisture in the crowns of trees or in the ground litter. Interception and transpiration by trees in a forest would thus tend to maintain drier soils and mitigate or delay the onset of waterlogged or saturated conditions in the soil.
Clear-cutting or felling of trees tends to produce wetter soils and faster recharge times following intense rainstorms.
Soil moisture stress and slope movement

Landslides and other catastrophic mass wasting events in mountain slopes are generally correlated with high precipitation and storm activity. The influence of precipitation on both creep movement and landslide occurrence derives from its relation to groundwater movement and soil moisture stress. The higher or the more prolonged the periods of elevated moisture stress in a slope, the higher will be the creep or accumulated creep movement.

Annual creep vs winter precipitation
A forest cover accelerates soil moisture depletion in a shallow soil mantle regardless of the steepness of the slope. For a simulated storm of a given intensity and duration, the recharge phase for the bare or denuded slope was therefore much shorter than for the forested one.

- therefore the first year after cutting is likely to be the most critical as far as soil moisture and its effects on slope stability are concerned.
Insights into the influence of tree cover on the soil moisture regime and hence on slope stability are provided by the results of a soil moisture monitoring study conducted in a forested site that was subsequently clear cut.

- indicate that the forest cover has little effect on the soil moisture regime once precipitation of sufficient duration and intensity falls on the slope and eliminates soil moisture suction.
- tree cover does not appear to have much influence on the probability of catastrophic sliding during intense storms. On the other hand, the soil moisture suction is definitely lower during the drier season of the year and accordingly creep movement and its destabilizing influence could extend over a longer period if vegetation removal results in substantially decreased soil moisture tension or suction over a large part of the year.
1. Root reinforcement
2. Soil moisture modification

3. **Buttressing and arching**
   4. Surcharge
   5. Root wedging
   6. Windthrowing

Buttressing and soil arching action by trunks of trees growing in slopes can also play an important role in slope stability. Buttressing or lateral restraint against shallow slope movement is provided by firmly anchored rigid tree trunks.

Deeply rooted Ponderosa pine tree buttressing and supporting a steep slope mass behind it. Unbuttressed portion of slope to left of tree has failed.
Tree trunks and their associated vertical root cylinders behave as potential abutments of soil arches which form upslope of the tree.

Arching in soil occurs when soil attempts to move through and around a row of trees firmly embedded or anchored in an unyielding layer. Under the right conditions the trees behave as cantilever piles and as the abutments of "soil arches" that form in the ground upslope of the trees.
In stable conditions the total force from upslope soil bearing against a tree embedded in a slope should be less than the combined pull-out resistance of the tree parallel to the slope and the passive resistance developed by the downslope soil mass.

In the case of a tree at or near a potential slope failure site, it is reasonable to assume that the presence of the tree can be beneficial if the resisting forces (ie the pull-out resistance parallel to the slope and passive resistance from downslope) are greater than the forces developed due to the upslope soil arching and/or the impact force developed due to the soil mass moving from an upslope failure.

The pull-out resistance of a tree can be considered as a function of the root morphology and strength. In order to evaluate the root anchorage, soil arching and buttressing effects of a tree on a slope, the determination of the pull-out resistance of the tree parallel to the slope is important.
1. Root reinforcement
2. Soil moisture modification
3. Buttressing and arching
4. **Surcharge**
5. Root wedging
6. Windthrowing

---

**Tree surcharge** is an estimate of the tree mass (biomass) that adds additional load to the failure surface.

Surcharge from the weight of trees is widely believed to have an adverse influence on the stability of slopes. This view is not generally correct; it is only true in special cases. In some instances surcharge can actually improve stability.

Researchers have studied the mechanics of landslides on forested uplands and include tree surcharge as an important component of overall hill slope stability. Realistic input parameter values usually assume the weight of trees are applied uniformly over the slope.
Surcharge on slope increases both the normal and downhill force components on a potential slip surfaces. In basic terms, surcharge has net stabilizing influences when the slope angle is less than the angle of internal friction of the soil.

\[ W_n = W \cos \beta \]

Stabilizing component
\[ W_n \tan \phi = W \cos \beta \tan \phi \]

Destabilizing component
\[ W_t = W \sin \beta \]
In general, surcharge caused by the weight of trees will not be uniform or very high (except perhaps immediately beneath a tree).

• As an example consider the weight of Douglas fir trees growing on slopes of experimental watersheds in the Cascade range, Oregon. Mechantable volumes of timber in these watersheds average 50,000 to 65,000 board ft/ acres.

• When the weight of the trees is spread out over the entire slope, the surcharge is only 12-15 psf. On the other hand the surface loading stress under an individual trees is 1400 psf.

• If the tree are assumed to distribute their weight over a circular area of 75 sq. ft and are spaces approximately 30 ft apart - this surface loading stress (1440 psf) will produce a stress increase varying from 20 to 75 psf midway between trees at depths of 5 and 20 ft respectively.

• Thus, the influence of surcharge from the weight of trees on either creep rates or safety factors in long slopes is not likely to be very significant one way or another.
The surcharge weight of trees is usually not an important cause of slope failure.

Imagine a rotational slump failure. The effect of surcharge depends upon whether the weight of the tree is directed onto the portion of the failure that is more or less than 45°. If it is less than 45°, then the surcharge from the tree actually strengthens the bank against failure.

For this reason, the lower down a slope you plant the trees, the better for the prevention of mass failure (so long as you have rotational failures).

Modelling experiments have shown that, even in places where the typical failure plane is greater than 45°, planting trees can be beneficial. This is because, in those cases where the roots of the tree cross the failure plane, the extra strength provided by the roots far outweighs any surcharge effects of the trees.

Where the root ball of a tree is entirely within the potential failure block, the tree is likely to be so small relative to the size of the block that surcharge will not be important.

The only situation where surcharge could be a problem is in shallow slide–type failures, where one layer of sediment slides over another one. If all of the roots are enclosed in the top and the slide is over 45°, tree surcharge could accelerate the failure.

Trees are often considered to add an extra weight (surcharge) to a slope that will encourage slopes to fail. In reality, the weight of trees seldom plays a role.
1. Root reinforcement
2. Soil moisture modification
3. Buttressing and arching
4. Surcharge
5. **Root wedging**
6. Windthrowing

---

**Root wedging** refers to the tendency for tree roots to penetrate a soil or rock mass along cracks, fissures and channels thereby loosening and prying it apart likewise.
Root wedging is alleged to have contributed to slope failures, but evidence for this effect is scant and unconvincing.

An equally good case can be made for the beneficial influence of roots in tying slopes together and mitigating failure. In any event, judging by the preponderance of evidence from published field and laboratory studies, the beneficial effects of root systems far outweigh any possible adverse effects.
1. Root reinforcement
2. Soil moisture modification
3. Buttressing and arching
4. Surcharge
5. Root wedging

6. **Wind throwing**

**Wind throwing** is likely to affect slope stability adversely. Strong winds blowing parallel to the ground surface exert an overturning movement on trees.
Wind is a major disturbance agent in the British Columbia Coast Mountains.

The effects of strong winds on trees range from loss of foliage and branches to small gap formation to partial or complete overstory blowdown. The heavy precipitation that tends to accompany storm systems saturates soils, reduces root adhesion, and increases the weight of tree crowns and thus makes trees more susceptible to damage.
A more common phenomenon is the uprooting or overturning of individual trees during high winds. When a tree with roots extending into mineral soil is uprooted by wind, a large mass of soil and rock is lifted with the roots thus producing a pit. As the fallen tree decays, the uprooted soil, roots, and stem settle to form a mound. The mound is leeward of the pit in the direction of the tree fall.
If it were assumed that wind generated shear stresses acted directly downslope and that the affected a significant portion of the slope at a given instant, a significant destabilizing force could theoretically be imposed on a vegetated slope. These symptoms are rarely met, however.

Nevertheless, wind through its effect on uprooting or swaying of trees may trigger soil mass movement on steep slopes. Uprooting of trees contributes to movement downslope of the soil and rock mantle and may initiate local gully type erosion. Swanston (1967) found that the majority of debris avalanches on shallow, colluvial soils occurred on timbered slopes and originated in areas of windthrown trees.
Consequences of Tree Removal on Mountain Slope Stability

- woody vegetation growing on slopes reinforces soils and enhances stability, conversely its removal should weaken soils and destabilize slopes.

- clear-cutting on mountain slopes warrants scrutiny in this regard, as it can result in denuded sites which are vulnerable to both erosion and mass movement.
Steep mountain slopes underlain by weak rock and soils are particularly sensitive to disturbances such as road building, clear-cutting and vegetation manipulation. Many investigators maintain that road building associated with logging plays the dominant role in slope stability problems.
Recognition that timber harvesting on steep slopes results in subsequent destruction of stabilizing root systems and can contribute to occurrence of shallow landslides.
Forested slope

- Wind
- Evapotranspiration
- Decreases w. t.
- Decreases soil cracking
- Apparent cohesion of roots
- Surcharge

Decreasing factor of safety -
Increasing factor of safety +
One year after clearcutting
Five years after logging

- Water table high
- Increased soil cracking
- Decreasing factor of safety
- Increasing factor of safety

- No surcharge
- Loss of root cohesion
- w.t.
Plot of mean maximum tensile strength against time elapsed since tree felling for roots <20 mm diameter and roots <18 mm diameter.
Comparative relative root reinforcement changes after clear felling (at year 0) and planting (at year 1). Growth curve represents an initial natural establishment density of 16 000 stems ha\(^{-1}\). Growth curves (2), (3) and (4) represent initial planting densities of 1250 stem ha\(^{-1}\), 800 stems ha\(^{-1}\), and 400 stems ha\(^{-1}\), respectively.
Post-fire landslide hazards include fast-moving, highly destructive debris flows that can occur in the years immediately after wildfires in response to high intensity rainfall events, and those flows that are generated over longer time periods accompanied by root decay and loss of soil strength.
Case Study: Kuskonook Creek, Purcell Mountains

Kuskonook Creek is a small drainage located in the Purcell Mountains of southeastern British Columbia, Canada. In the summer of 2003 a major forest fire occurred within the catchment. In August 2004 a localized rainfall event occurred in the general area and triggered a debris flow that deposited a large volume of debris on the fan. A second, much smaller, more fluid debris flow occurred in September 2004.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area (km²)</td>
<td>4.2</td>
</tr>
<tr>
<td>Highest catchment elevation (m)</td>
<td>2135</td>
</tr>
<tr>
<td>Fan apex elevation (m)</td>
<td>600</td>
</tr>
<tr>
<td>Melton ruggedness factor</td>
<td>0.75</td>
</tr>
<tr>
<td>Kootenay Lake elevation (m)</td>
<td>535 (varies with season)</td>
</tr>
<tr>
<td>Average main channel (Branch A) gradient (degrees/%)</td>
<td>19/35</td>
</tr>
<tr>
<td>Tributary (Branches B, C and D) gradients (degrees/%)</td>
<td>35/70–6/10</td>
</tr>
<tr>
<td>Fan area (km²)</td>
<td>0.05</td>
</tr>
<tr>
<td>August 2004 debris deposit gradient on fan (degrees/%)</td>
<td>11/19–8/14 (average 8.5/15)</td>
</tr>
</tbody>
</table>
In the summer of 2003, a major forest fire occurred within the Kuskonook Creek catchment and the adjoining areas to the north and east. The forest fire affected almost the entire catchment. Approximately 50% of the upper catchment was severely burned and an estimated 10% was intensely burned. The intense burning resulted in the creation of hydrophobic (water repellent) soils.

- Note: hydrophobic soils are devoid of vegetation and have been physically altered so that water runs off very quickly with very little infiltration
During the night of August 6/7, 2004 a localized rainfall occurred in the general area and triggered a debris flow that deposited 20,000–30,000 m$^3$ of debris on the fan.

The debris flow resulted in the destruction of two houses, a heritage building and a water supply system. Substantial damage occurred to several other buildings, several unoccupied parked vehicles and a power pole. The debris flow overran and closed a subdivision road and provincial Highway 3A for several days.
At approximately 1,800–2,050 m elevation in an intensely burned area, there was abundant evidence of overland water flow and some erosion. Most of the overland flow occurred on relatively gentle slopes then cascaded over steep slopes toward the incised gully of the main channel.
Debris flow initiation factors

A series of events led to the August 2004 debris flow. These included: – the forest fire of 2003,
– the rainfall immediately prior to the event, and
– sediment accumulation since the last large debris flow event.

The relationship between forest fires and debris events is well documented in areas with similar soil, climate and forest type to Kuskonook Creek. Depending on the intensity of the fire, antecedent soil moisture, and thickness and properties of the organic forest floor material, hydrophobic (water repellent) soils can be created. This was the situation with the 2003 Kuskonook Creek forest fire.

Most debris flows that are the result of forest fires occur in the first 2 years after the fire. Sediment erosion occurs when high runoff entraps sediment creating a progressive bulking of runoff and sediment. Recent research in the Pacific Northwest has determined that 4 years after a forest fire has occurred, excess sediment and runoff caused by an intense burn essentially no longer occurs.
Sediment accumulation since the last large debris flow

There are no anecdotal records of any debris flow, debris flood, or water flood events on Kuskonook Creek during the past 110 years of continuous settlement. Based on dendrochronology the oldest trees on the fan, growing on top of debris from a previous debris flow, vary in age from approximately 76 to 108 years.

The rate of tree growth indicates that several of the trees had grown in open conditions. This is consistent with the history of possible clearing of trees from the fan in the late 1800s for construction and settlement purposes, and the known 1900 fire that presumably affected any remaining trees along with the neighbouring buildings.
The modification of mountain slopes, particularly deforestation and the disturbance of the soil cover and the soil profile, was very common in the earliest development of ski runs. Negative effects on the environment were usually neglected. However, the effects were rather severe especially in higher areas, where natural restoration is restricted by the extreme climatic situation and constrained conditions for vegetation and re-growth.

Nevertheless, as the demand for skiing and attractive skiing facilities increases, there are continuing impacts caused by new skiing facilities that require attention and management of ski slopes.
Horstman Glacier
• landscape altered because of clearings for ski slopes and facilities.
• altered from a purely forest to a rock-soil landscape.
• climate and the high altitude facilitate the wind and rain erosion of the soil.
• this can be further accelerated by the frequent machine maintenance of the ski slopes.
Diagram showing the effects of ski runs on the environment.

Precipitation intercepted by trees.  No protection, erosion occurs.  Increased run-off.  Intercepted.

Ski runs with no snow on them leave bare soil slopes out of the ski season.
Degradation of a rock glacier in the Sölden ski area – left side of the mountain in the centre: destroyed; right side: no disturbance.
A rotational landslide on the lower margin of a ski-run. This ground failure was mainly caused due to high water pore pressure from meltwater. Because the artificial margin of the ski-run was just about 2 m higher than the natural margin and the gentle slope below the ski-run, the probably slow moving mass stopped already at the bottom of the short ski-run slope.
A shallow translational slide on the upslope edge of a ski-run. The white arrows indicate the area of release.
A generalized representation of a part-forested slope. The forces resisting failure depend on the soil strength plus the additional soil reinforcement supplied by root soil cohesion. The forces promoting failure depend on the weight of soil and trees, slope angle, and wind force.
Variations in northern hemisphere temperatures for the past 1000 years

95% confidence limits in grey

Data from thermometers (red) and from tree rings, corals, ice cores and historical records (blue).
Temperature Rising
Climate Change in Southwestern British Columbia