THE EFFECT OF THE MOUNTAIN PINE BEETLE ON SLOPE STABILITY, SOIL MOISTURE AND ROOT STRENGTH

by

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ABSTRACT

The mountain pine beetle (MPB) has caused significant tree mortality within North America. This work explores the impact of such unprecedented tree mortality on slope stability. Within the first growing season following infestation, transpiration ceases; thus saturation increases, adding a driving force to slope failure. The increase in saturation was the primary driver for the decrease in the Factor of Safety. The hydrologic properties were modeled using ParFlow. As the trees and roots decay, the root tensile strength decreases by 0.2μPa within the first few years of mortality. The combination of the decrease in root tensile strength and the increase in saturation were used to assess the impact of MPB mortality on slope stability through examining changes in the Factor of Safety using an infinite slope model. From a sensitivity analysis, the largest change in the Factor of Safety (a decrease of 5%) was observed at the lowest angled hillslopes.
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Slope stability is defined as the potential for a slope to withstand or undergo movement. Within Colorado, slope stability is a critical issue due to the fact that climate, slope, and geologic conditions influence movement, such as landslides (Yuhas et al., 1982). The consequences of a slope failure include but are not limited to: changes in water availability and quality, damage to structures, and human fatality. In the United States, landslides are responsible for causing an estimated $1 billion in damages and 25 to 50 deaths each year (USGS, 2014). Through understanding the implications of land movement and quantifying slope stability, the impact of slope failure can be reduced and the infrastructure can be improved to handle these hazards.

The following factors are known for reducing slope stability: an increase in saturation, a decrease or decay of vegetation, loading of the head, and/or cutting the toe of the slope. Changes in saturation and vegetation reduce the frictional forces acting on the slope. Through loading the head of the slope, additional driving forces are added to the slope. If the slope is in equilibrium, cutting the toe of the slope changes the slope geometry, which in turn impacts how the forces are distributed within the slope. These four factors have been known to most commonly change through large scale land disturbances.

Two common large-scale land disturbances that are known to impact slope stability are fire and clear cutting. There are physical changes to the slope in both processes. Clear cutting results in a high percentage of tree mortality. As with fire, trees are scorched and there is the loss
of understory vegetation. Due to loss of interception, transpiration, and increased snow accumulation there is a change in soil saturation (Anderson et al., 1976). The roots decay in both scenarios and reduce the cohesion of the soil (Gray, 1978; Ziemer 1981). Overall, studies have shown the compilation of these changes has directly reduced slope stability (Gray & Megahan, 1981). A recent large-scale land disturbance within the region is the Mountain Pine Beetle. Forest mortality from the MPB and subsequent changes in soil moisture and root structure also has the potential to reduce slope stability in the steep, landslide-prone region of the Rocky Mountains.

The mountain pine beetle (MPB), *Dendroctonus ponderosae*, has caused significant tree mortality across North America, with the strongest effects of the mortality along the Rocky Mountains spanning from New Mexico to British Columbia (Edburg et al, 2012). Since 1996, approximately 3.4 million acres of lodgepole, ponderosa, and five-needle pines have been impacted by the outbreak in Colorado (Figure 1.1) (Colorado State Forest Service, 2015). The MPB preferentially affects larger diameter trees, which has a greater effect on the overstory canopy (Edburg et al., 2012). In some locations, the MPB has destroyed ninety percent of overstory canopy structure and seventy percent of basal area (Collins et al., 2011).

The exceptionally high mortality rate of the most recent MPB outbreak can be attributed to environmental stresses experienced by forests in the past two decades. Normally, trees defend themselves by expelling sap and forcing the MPB to retreat from the tree. This natural defense against MPB has been reduced due to increased drought (Bentz et al., 2010), coupled with warmer winter temperatures (Mitton & Ferrenberg, 2010). When temperatures drop below −40°C
there is a 100% mortality rate within the beetle population (Carroll, et al., 2004). With warmer winters, this means that the temperature does not reach this threshold and there is less winter die-off. Due to the fact that regional temperatures have increased in recent years, the MPB is now able to produce two generations every year, with the flight season beginning more than a month earlier than in the previous two decades (Mitton & Ferrenberg, 2010). The recent increase in temperature is also responsible for the MPB’s ability to move to higher elevations and latitudes (Logan et al., 2010). As the MPB destroys monoculture lodgepole stands, the MPB is forced to spread to new locations.

**Figure 1.1:** MPB impact within Colorado, USA for the past 20 years (1995-2015). This figure displays the impact on ponderosa pine and lodgepole pine. The data is from the USDA Forest Service. The location on the map symbolizes where the root testing occurred, Officer Gulch, CO.
The MPB burrows into the bark of a tree causing the tree to secrete resin from the borehole and form pitch tubes. The MPB has a symbiotic relationship with *Grosmannia clavigera*, known as the blue stain fungus. As the fungus germinates within the bark, it spreads to the tree’s xylem, causing water transport in the tree to cease (Hubbard et al., 2013). Once a tree has been infested with MPB, there are three phases of mortality: Green Phase, Red Phase, and Gray Phase (Edburg et al., 2012). In the Green Phase, the tree is able to defend itself, evapotranspire, and uptake groundwater. By the end of the first growing season following infestation of MPB, a tree will enter the Red Phase, when transpiration will cease and the tree will slowly begin to lose its needles (Hubbard, 2013, Mikkelson et al., 2013). Through the rapid decline of transpiration during the Red Phase, local soil moisture may increase (Morehouse et al., 2008). The Gray Phase occurs two to three years proceeding initial infestation as the tree’s normal functions cease and the needles fall from the tree (Wulder et al., 2006). The loss of needles causes canopy openings, which alters throughfall and the radiation balance at the ground surface (Molotch et al., 2009; Vanderhoof et al., 2013). In addition, these openings remove competition for resources, space and sunlight; allowing regrowth of new trees, smaller shrubs, forbs and grasses (Stone & Wolfe, 1996). The changes in evaporation, transpiration, and radiation fluxes can be seen in Figure 1.2.

The MPB also affects the root systems of pines throughout the three phases. Normal processes continue during the Green Phase. During the Red Phase, root respiration will decrease, as carbon allocation underground is initially low following the infestation (Goulden et al., 2011). An increase in soil moisture enhances root decomposition; thus, there is a predicted increase in nitrogen availability with infestation-induced soil moisture increases (Edburg et al., 2012). The
supply of nitrogen in the soils may be driven by the reduction of living roots in the subsurface 
(Griffin et al., 2012). Due to the MPB disturbance, the shallow, fine rootmass has been shown to 
decrease by half, with an increase in tree mortality (Cigan, et al, 2014).

Figure 1.2: A: Infested trees cease to transpire in the first growing season following infestation 
(Bearup et al., 2014); therefore, as the tree begins to decay the root tensile strength decreases. In 
addition, the rise of the water table, from the lack of transpiring trees, adds a driving force to the 
slopes. The arrows symbolize groundwater uptake, soil evaporation, and transpiration. B: The 
cross-sectional view of the model set-up displaying saturated/unsaturated zones, root/sub-root 
zone, soil/bedrock units.

Quantifying the rate of decay of the tree roots is important because healthy tree roots 
provide shear resistance to hillslopes through tensile strength. This is due to the fact that soil 
strength increases linearly with root biomass (Ziemer, 1981). Previous studies documented an 
increase in landslide frequency from root deterioration (e.g. O’Loughlin, 1982, Schmidt et al., 
2001). For a lodgepole pine root system, a taproot is developed when it is young that is replaced
by a lateral root system as the tree grows, although the exact framework of the root ball depends highly upon the quality of the surrounding soil (Koch, 1996). The high density of lateral roots of the lodgepole pine near the surface contributes to an increase in soil strength (Lu et al., 2012). This means that the extensive lateral roots, of large diameter lodgepole pines that are targeted by MPB, contribute highly to the soil strength.

The roots will continue to decompose until ultimately causing snag fall. Snag fall occurs when the roots can no longer bear the weight of the tree so the tree topples. After two years, in Colorado, trees fell at a rate of 3-5% per year due to the MPB (Schmidt et al. 1985). Proceeding snag fall, the decay rates accelerate (Lewis & Hartley, 2006). This creates a large loss in the density of the tree roots in the subsurface. Quantifying the abundance of snagfall will improve the understanding of the impact of the MPB on slope stability.

In addition to physical changes to the tree, the MPB affects the hydrologic cycle, biogeochemical cycle, and energy budgeting. MPB literature contains multiple reviews that focus on these changes through conceptual models, modeled hydrologic changes, observed and modeled biogeochemical and hydrologic responses (Adams et al., 2012; Edburg et al., 2012; Mikkelson et al., 2013; Pugh and Gordon, 2013). The compounding effects of decreases in transpiration and interception lead to heightened soil moisture content under the impacted trees (Clow et al., 2010; Morehouse et al., 2008). Subsequence loss of needles results in greater throughfall but also increases the amount of radiation that reaches the ground (Mikkelson et al., 2013, Chen et al., 2015), resulting in increased soil evaporation, which can compensate for transpiration reductions. In addition, these changes in radiation exposure can increase snowmelt
and sublimation rates. These rates occur more rapidly under beetle infested trees than healthy ones, due to canopy loss and increased radiation and at an earlier time of year (Mikkelson et al., 2013); however, due to lack of interception, snow may accumulate more under beetle-killed trees (Pugh & Small, 2012). On the other hand, Biederman et al., 2012, through water isotope data, showed higher snowpack sublimation rates during the Grey Phase, yet no difference in peak SWE under Green and Grey stands. At the hillslope scale, the increase of soil moisture under impacted trees, rapid snowmelt, and adjustments to the timing of spring runoff all have the potential to influence driving forces that can impact slope stability.

Slope stability is the ability of a slope to resist motion and is normally quantified as the ratio of resisting (frictional) forces over driving (gravitational) forces, also known as the Factor of Safety. If the Factor of Safety is below one, the likelihood of mass movement is highly probable. For this research, the Factor of Safety was calculated using an infinite slope assumption based on limit equilibrium analysis along a presumed failure plane. The relationship between soil properties and the failure plane can be assumed to be linear as calculated by Mohr-Coulomb stress criteria. The Factor of Safety is computed on a grid across a slope that is assumed to be homogeneous and consistent thickness above the slide plane (Lu, et al., 2008).

Water content plays a large role in slope stability. As mentioned above, increase in soil moisture and snowpack add weight to the surface. This supplies a driving force to the system, reducing the overall Factor of Safety. Water is able to fill and exert pressure on the void spaces reducing the cohesion of the soil, adding weight, and increasing the driving forces. Water in the
voids also reduces the coefficient of friction, reducing the resisting forces. Increasing the soil moisture under impacted trees can have large implications in terms of slope stability.

This research aims to identify a correlation between slope instability and the locations of MPB tree mortality. The approach is threefold: (1) quantify the in-situ tensile strength of lodgepole pine roots as a function of time; (2) combine the change in tensile strength with the results of a hillslope model to investigate the ecohydrologic conditions under which the MPB will impact slope stability; and (3) complete a sensitivity analysis in order to identify the main controls on the slopes that the MPB is impacting. Through this analysis, insight on the decay rate of the tensile strength of tree roots will be examined. A hydrologic model in ParFlow-CLM will be developed to study changes in pore pressure and saturation to the hillslopes. The goal of this model is to test whether the impact on the tree roots and changes in saturation are enough to significantly impact a slope’s Factor of Safety. It is hypothesized that root decays through time due to both the deterioration of the tree and increase in soil moisture (as displayed in Figure 1.3).

![Figure 1.3](image_url)  
**Figure 1.3**: Hypothesized response of the disintegration of lodgepole pine roots when impacted by MPB. Soil moisture curve constructed from Morehouse, 2008.
CHAPTER 2

MATERIALS AND METHODS

2.1 Tensile Strength of Lodgepole Pine Roots

Officer Gulch, west of Frisco, CO, was selected to collect field data (Figure 2.1). At this location, there is an abundance of MPB mortality ranging over multiple years. The forest age, density, and growth allowed for ideal testing conditions. The geologic unit in the area is igneous bedrock overlain by glacial deposits at lower elevation. In addition, at this location variables such as slope aspect and tree breast diameter were held constant.

Tree root strength can be quantified through in situ field-testing of tensile strength. Previous studies demonstrate that 1 to 10 mm diameter roots are most effective in sustaining the stability of timbered slopes; therefore, 2-4 mm roots were selected for the tensile strength test (of the green, red, gray phase roots) (Burroughs et al., 1997) (Figure 2.2). In addition, cellulose is tension resistant; thus, thin roots are much stronger than thicker roots, which have a large non-cellulose component (Genet et al., 2005). The 80 roots were sampled in the field and then tested immediately for tensile strength, recording the weight required to break the root. If the root broke along the clamps, the test was disregarded. The apparatus used to test the roots was a fish scale with quick grip clamps (Figure 2.2).
Figure 2.1: Officer Gulch study areas assessed for the tensile strength of roots. The trees that were used for the analysis are marked in pink triangles.
For consistency, lodgepole pines with a diameter at breast height of 30-48 cm and root diameter of 2-4 mm were considered for the test. Only areas with similar geology and soils were considered for testing. The south/east facing slopes were tested due to the lack of soil development that tends to occur on these slopes which affects the root structure.

From this data, the tensile strength was calculated from the following equation (Schmidt et al., 2001):

$$T_{rl} = \frac{F_r}{A_r}$$  \hspace{1cm} (2.1)

where $T_{rl}$ is the tensile strength of the root [N/mm$^2$]; $F_r$ is force needed to break the root [N]; and $A_r$ is cross-sectional area of the root [mm$^2$].

Equation 2.1 neglects the interaction of the soil and roots because root cohesion is limited by the strength of the roots, not the bond between the roots and the soils (Schmidt et al., 2001). Thus, root tensile strength is the limiting factor and is used in the remainder of the calculations.
To account for the volumetric differences between the roots and surrounding soil, a sieve analysis of a glacial loam within the Rocky Mountains was used (Fahey et al., 1988) to estimate the root density. The root zone is designated at 0-0.4m, as this is the location of 90% of the tree’s roots (Fahey et al., 1988). The sub-root zone is calculated up to 1.0 m in depth. This will be further elaborated upon when adding root cohesion into the infinite slope model at different depths within Section 2.2. The volumetric content of roots to soil is important due to the fact that the total tensile root-strength is calculated per unit volume (Equation 2.2). The volume of roots to soil in the root zone and sub-root zone was 0.497 and 0.235, respectively (Fahey et al., 1988).

\[ tr_i = \sum_{i=1}^{n} \frac{V_r}{V_s} T_{ri} \]  

(2.2)

where \( tr_i \) is root thread strength per unit volume of soil \([\text{N/mm}^2]\); \( V_r \) is volumetric root content \([\text{mm}^3]\); and \( V_s \) is volumetric soil content \([\text{mm}^3]\).

Allowing the tensile strength to then be calculated based on the tangential and normal components of the roots, the reinforcing strength provided by roots (\( C_r \)) can be described by:

\[ C_r = \sum tr_i (\sin \theta + \cos \theta \times \tan \alpha) \]  

(2.3)

where \( C_r \) is the reinforcing strength provided by roots \([\mu \text{Pa}]\); \( tr_i \) is the root tensile strength of root \( i \) at the landslide shear plane \([\text{N/mm}^2]\); \( \theta \) is the slope gradient \([^\circ]\); and \( \alpha \) is the angle of internal friction of the soil \([^\circ]\) (Ziemer et al., 1991).
The overall cohesion of the soil in the root- and sub-root zone was added to the calculation for the infinite slope model in order to quantify the changes in root tensile strength on slope stability.

2.2 Integrated Hydrologic Modeling

Integrated hydrologic modeling involves coupling surface and subsurface flow equations in order to resolve land-energy and water balances (Maxwell et al., 2014). ParFlow is an integrated hydrologic model that is able to model the transient hillslopes used for this simulation. ParFlow solves variably saturated subsurface flow (using Richards’ equation) integrated with overland flow (Manning’s equation) (Jones & Woodward, 2001; Kollet & Maxwell 2006; Maxwell 2013). ParFlow is fully coupled with the Common Land Model (CLM) which simulates surface vegetation and land surface processes (Maxwell & Miller, 2005; Kollet & Maxwell, 2008).

MPB impacted slopes were modeled with a two-dimensional model at the hillslope scale. The model consisted of a 5m thick bedrock unit overlain by soil, 4m thick (see the cross-sectional column in Figure 1.2.B). The bedrock was an igneous crystalline bedrock which is representative of the bedrock seen in the field. Four soils were chosen based on their variety of cohesion, hydraulic conductivity, porosity, and specific storage: gravel, sandy clay loam, loamy sand, and silt loam. The ParFlow model was used to simulate two scenarios: an undisturbed forest cover simulation and a simulation with complete beetle mortality (as in Mikkelson et al., 2013; Penn et al., 2016 and Bearup et al., 2016). These two scenarios were driven by hourly weather data for water year 2008 in Breckenridge, CO (NLDAS, 2008). The model was spun up
for ten years and the water balance over the water year was within 0.02%, meaning that the beginning and ending subsurface storage were the same and the simulation had reached a dynamic equilibrium. More details on the properties of material, weather, model set-up, and vegetation parameters are listed in Table 2.1.

The outputs of the integrated hydrologic model and root tensile strength were then combined into an infinite slope stability model. Various model types were considered, but the infinite slope model was selected because its assumptions accounted for both saturated and unsaturated conditions (for detailed comparison, see Appendix A). The ParFlow outputs of hydraulic pressure head and saturation were input into the slope stability model to account for changes in ground-water table and soil suction strength. In addition, the root zone was broken down into a root zone (2m in thickness) and a sub-root zone (3m in thickness) based on volumetric root content (see cross sectional breakdown in Figure 1.2.B).

The premise of the infinite slope model developed a grid across the hillslope and calculated the Factor of Safety in each grid cell (Lu, et al., 2008). The infinite slope model assumes there is a linear failure plane (Das, 2013). The method also separates how to calculate the Factor of Safety under saturated and unsaturated conditions (Baum et al., 2002). The saturated Factor of Safety was calculated using the following equation:

\[
FS = \frac{\text{tan} \phi' - \psi (b, t) / \gamma_w \tan \phi'}{\text{tan} \alpha / \gamma_s \sin \alpha \cos \alpha}
\]

(Taylor, 1948; Godt 2008)

where \(FS\) is the Factor of Safety; \(b\) is the height [m]; \(\alpha\) is the slope angle [°]; \(t\) is time [Hours]; \(c'\) is cohesion (soil cohesion + root cohesion) [kPa]; \(\psi\) is pressure head [m]; \(\phi'\) is internal angle of friction [°]; \(\gamma\) is (soil/water) unit weight [kg/m³]; and \(\theta\) is (volumetric/saturated/residual) water content [m³].
Table 2.1: Soil, Vegetation, and Model Parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Properties</th>
<th>Value</th>
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<td>Cell Discretization (x, y, z)</td>
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<td>Number of Cells (x, y, z)</td>
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<td>Slopes (°)</td>
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<td>Precip, temp, rel. humidity, wind, pressure,</td>
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<td>ParFlow Parameters</td>
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<td>Van Genuchten α (1/m)</td>
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<td>Parameters</td>
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<td></td>
<td>Cohesion (Kpa)</td>
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</table>

(Association of Swiss Road and Traffic Engineers; Chow, 1986; Domenico et al., 1990; Gomes et al., 2011; Guarracino, 2006; Jaeger et al., 1976; ; MDOT, 2013; NAVFAC, 1986; Saxton et al., 2005; Shapp, 1998; Trekova, 2005; Wang et al., 2013)
The unsaturated Factor of Safety was calculated using the following equations:

\[
FS = \frac{\tan \phi'}{\tan \alpha} + \frac{2c'}{\theta_b \sin 2\alpha} - \frac{\sigma_s}{\theta_b} (\tan \alpha + \cot \alpha) \tan \phi'
\]  
(2.5)  
(Godt, Baum, Lu, 2009)

The suction stress was calculated as:

\[
\sigma_s = \frac{\theta - \theta_r}{\theta_s - \theta_r} (u_a - u_w) = -S_v (u_a - u_w)
\]  
(2.6)  
(Godt, Baum, Lu, 2009)

\(FS\) is Factor of Safety; \(b\) is height [m]; \(\alpha\) is slope angle \(\left[^\circ\right]\); \(c'\) is cohesion (cohesion + root cohesion) [kPa]; \(u\) is pore pressure [m]; \(\phi'\) is internal angle of friction \(\left[^\circ\right]\); \(\gamma\) is (soil/water) unit weight [kg/m\(^3\)]; \(\theta\) is volumetric water content; \(\theta_s\) is saturated water content; and \(\theta_r\) is residual water content.

2.3 Sensitivity Analysis of Factor of Safety Calculations

In order to fully understand the results of the Factor of Safety infinite slope model, a sensitivity analysis was completed. Because slope stability calculations are directly impacted by the angle of the slope, and the surface and subsurface processes change with varying degrees of slopes, a sensitivity analysis compared different angles of slopes ranging from 5-30 degrees. The soil types chosen are from a range of soil properties that will impact both the hydrologic calculations and Factor of Safety calculations, including hydraulic conductivity, porosity, residual saturation, specific storage, van Genuchten parameters, Manning’s number, unit weight, internal angle of friction, and cohesion.
CHAPTER 3

RESULTS

3.1 Tensile Strength of Lodgepole Pine Roots

The in situ, tensile strength measurements from the field were separated into three groups based on the phase of beetle mortality: Green Phase, Red Phase, and Grey Phase. Red Phase measurements were not compared here because a significant number of Red Phase trees were not available for testing within the field site. When physically breaking the roots, there was a distinct difference in moisture content of the roots in the Green Phase (high moisture content) and the Grey Phase (low moisture content). Overall, the trees in the Green Phase and Grey Phase were clumped as a single data set within each group, regardless of the estimated time since infestation for the Grey Phase. The data collected is non-parametric; therefore, Kruskal-Wallis method of calculating a p-value was used to calculate a p-value of 0.1 (Daniel, 1990). Thus, there is evidence that the Green and Grey Phase root tensile strength calculations are distinct populations. A box-and-whisker plot of the tensile strength of Green and Grey Phases can be seen in Figure 3.1.

The results displayed a decrease in the median of tensile strength between the Green and Grey Phases of 0.2 μPa. There is also a wide amount of variability that is associated with the collected tensile strength. This is due to the fact that within the Green Phase, the tree health was not taken into consideration. For instance, the closer the tree was to the perennial stream within the field site the higher the moisture content and the higher the tensile strength. Within the Grey Phase, the wide bounds can also be explained from the lumping together of all of the years since
infestation rather than parsing out each individual year. When plotting the decline of the tensile strength through time, there was a decrease in strength from the Green Phase to Grey Phase; however, a steady, linear decline of tensile strength was not observed.

![Tensile Strength](image)

**Figure 3.1:** Box and whisker plot of the Green and Grey phase tensile strength ($p = 0.1$).

### 3.2 Integrated Hydrologic Modeling

The ParFlow model was developed for four different soil types (sandy clay loam, silty loam, loamy sand, and gravel) across four different slope angles (5, 10, 20 and 30 degrees) for both the Green and Grey Phase, resulting in a total of 32 scenarios. Each scenario was spun up until the annual change in subsurface storage was less than 0.1% to ensure that groundwater tables were representative of hillslope conditions.

Within the model, the total saturation of the soil and bedrock was averaged spatially through the hillslope and then plotted through water year 2008 as displayed for the sandy clay
loam in Figure 3.2. Modeled saturation is consistent with seasonal trends in the region. The total saturation reflects the accumulation of snow November-June with the steady decline in saturation of the soil during this time period. Following snowmelt, there is an abrupt increase in soil moisture starting in mid-June through mid-July. This is the largest increase in saturation over the shortest period of time. The saturation then continues to level out through the remainder of the summer months. There is a large precipitation event in mid-September that causes a small peak increase in saturation.

Overall, the Grey Phase saturation was higher than the Green Phase saturation. The saturation response to the snowmelt was both higher and earlier in the Grey Phase model. However, the timing of saturation response for snowmelt and precipitation events is the same. In both the Green Phase and Grey Phase, peak saturation occurred on the same day. This was consistent throughout all four soil types at all angles of slope.

As the angle increased, the average saturation decreased throughout the slope (more water was running off rather than infiltrating into the soil). As the slope angle increased, the difference between the Green Phase and Grey Phase decreased, especially during the winter months. The slope angle did not impact the time at which peak saturation occurred or the magnitude of response to snowmelt and precipitation events. With increasing angle, saturation differences decrease (i.e., the overall saturation difference between 5 and 10 degree slope is larger than the difference between 20 and 30 degrees). For steeper slopes, the changes in saturation would be even smaller (due an increase in overland flow instead of infiltration) which is why 30 degrees was used as a cutoff angle for the models.
Figure 3.2: Hourly saturation throughout the year spatially averaged over the hillslope. The saturation is plotted for the Green and Grey Phase across the different angles ranging from 5-30 degrees. Note that as the slope angle increases, the saturation decreases. In all of the scenarios, the saturation in the Grey Phase is larger than the saturation in the Green Phase. In addition, the difference between the Green and Grey Phases is less.

3.3 Sensitivity Analysis of Factor of Safety Calculations

Comparing the Factor of Safety across different soil types and angles as a spatial average is displayed in Figure 3.3. This plot displays a 1:1 relationship with the average Green Phase and Grey Phase Factor of Safety across the entire hillslope. This linear relationship shows that when the Factor of Safety is averaged across the slope, the changes are relatively small.

The slope angle is the primary control of the Factor of Safety across the hillslope. The Factor of Safety decreases with an increase in slope angle. The soil type is a secondary control on the Factor of Safety with a Sandy Clay Loam producing the lowest Factor of Safety and Loamy Sand...
producing the highest Factor of Safety. At higher slope angles, the soil type has less effect on the Factor of Safety.

![Diagram](image)

**Figure 3.3:** This plot compares the 1:1 relationship of the Factor of Safety in the Green Phase and Grey Phase.

The quantitative differences in the changes of Factor of Safety are displayed in Table 3.1. The Factor of Safety for the entire hillslope was averaged and then the Grey Phase average was subtracted from the Green Phase average. Although small, there was a decrease in Factor of Safety from Green Phase to Grey Phase. The highest change in the Factor of Safety from Green Phase to Grey Phase occurred in the five degree slope of the sandy clay loam. There was a general trend that as the slope angle increased, the change in Factor of Safety decreased. Gravel had the lowest changes in the Factor of Safety while the Sandy Clay Loam contained the highest changes in Factor of Safety.
### Table 3.1: Difference in Grey-Green Phase Factor of Safety

<table>
<thead>
<tr>
<th></th>
<th>Sandy Clay Loam</th>
<th>Silt Loam</th>
<th>Loamy Sand</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-0.0075</td>
<td>-0.0048</td>
<td>-0.00359</td>
<td>-0.00107</td>
</tr>
<tr>
<td>10</td>
<td>-0.00372</td>
<td>-0.00295</td>
<td>-0.00162</td>
<td>-0.00109</td>
</tr>
<tr>
<td>20</td>
<td>-0.00201</td>
<td>-0.00162</td>
<td>-0.00085</td>
<td>-0.00095</td>
</tr>
<tr>
<td>30</td>
<td>-0.00147</td>
<td>-0.00142</td>
<td>-0.00055</td>
<td>-0.0009</td>
</tr>
</tbody>
</table>

The Factor of Safety decreases with increasing slope angles. On a five, ten, twenty, and thirty degree slope, the Factor of Safety was roughly fourteen, seven, three, and two, respectively. The interesting aspect of this change in Factor of Safety is the location at which it occurs. A cross section of the changes in the Factor of Safety, from Green Phase to Grey Phase, across all four slope angles can be seen in Figure 3.4. The location of the changes in Factor of Safety is most pronounced at the toe. As the lateral flow collects at the no flow zone at the base of the hillslope, there is a change in saturation at the toe. At the head of the slope, the changes in saturation are linear due to the difference in water table height from Green to Grey Phase. The changes at the head and toe of the slope are within the soil on top of the bedrock. The bedrock within the model is not impacted by changes in saturation; thus, the Factor of Safety from Green Phase to Grey Phase does not change for any points within the bedrock. As the slope angle increases, the difference between the Factor of Safety from Green Phase to Grey Phase decreases. In Figure 3.4.A. (5 degree hillslope), the maximum Factor of Safety difference between the Green and Grey Phase is 0.05 compared to Figure 3.4.D. (30 degree hillslope) with a maximum difference of 0.02. This displays that as the slope increase, the impacts from the MPB decrease (smaller changes in saturation from Green to Grey Phase); thus although steeper slopes are more prone to failure, they will not see the same impact in the change in Factor of Safety as the slope goes from Green Phase to Grey Phase.
Figure 3.4: Spatial patterns in Factor of Safety changes with tree death (Grey-Green) for sandy clay loam soil type at (A)5°, (B)10°, (C)20°, and (D)30° slopes. Note how the largest changes are located along the locations where the water table rose from Green to Grey Phase.

As displayed in Figure 3.6, there was a larger change in the Factor of Safety at the toe of the slope. This is directly reflected as the Factor of Safety is further broken down to look at the changes throughout the year at the toe and head of the slope (Figure 3.5). The changes in the Factor of Safety were plotted over Water Year 2008, showing an inverse relationship to saturation. These changes are ubiquitous across all soil types and slope angles.
Figure 3.5: Comparing the hourly saturation and Factor of Safety at toe (A) and the head (B) of the slope. The Factor of Safety is plotted for a 5 degree slope for a Sandy Clay Loam.
CHAPTER 4

DISCUSSION

4.1 Tensile Strength of Lodgepole Pine Roots

The decay of the roots causes a loss in tensile strength, which helps resist downslope movement. Once a tree ceases to transpire, the tensile strength of the roots begin to decrease over time (O’Loughlin et al., 1982). Due to the MPB disturbance, the shallow, fine rootmass decreased by half with an increase in tree mortality (Cigan, et al., 2014). However, this decrease in rootmass does not translate to large decrease in tensile strength. Investigating the timing of the decline in root strength from Green to Grey Phase provides better quantification of the effect of MPB on slope stability. The results displayed a decrease in the median of tensile strength between the Green and Grey Phases of 0.2 μPa (p = 0.1). However, the changes in tensile strength were of negligible magnitude when compared to the cohesion of the soil (the loamy sand, for example, was measured at 15 KPa (MDOT, 2013)). Root regrowth is adding cohesion to the hillslope. At a regional scale, there is inhibition when comparing the spatial locations of MPB infested areas and landslides (Appendix B). This could potentially be explained through regrowth increasing the cohesion of the soil, thus increasing the Factor of Safety of the hillslope. The conceptual model of the interaction between root decay, root regrowth and saturation can be edited in order to reflect the negligible differences in the tensile strength and emphasize the important of saturation when calculating the Factor of Safety through time of MPB decay (Figure 4.1).
Figure 4.1: Updated conceptual model displaying a reduction in the overall change in tensile strength throughout MPB root decay, in order to reflect the results. Soil moisture curve constructed from Morehouse, 2008.

4.2 Integrated Hydrologic Modeling

In all the model simulations, the Grey Phase saturation is higher than the Green Phase saturation. This is due to the fact that as the trees transform from Green to Grey Phase, they cease to transpire (Wulder et al., 2006), and are no longer taking up groundwater, resulting in greater water availability in the subsurface. In addition, there were changes in snow water equivalent (SWE). In the Grey Phase there was less interception and an increase in snowpack (Molotch et al., 2009; Vanderhoof et al., 2013). This increase in SWE at the tree to hillslope scale allows more water to infiltrate into the subsurface and is reflected within the model. It is also important to note that the timing of peak saturation, which correlates to peak snowmelt, is earlier in the year when the hillslope was modeled in the Grey Phase. The increase in saturation
from Green to Grey Phase is similar in magnitude to previous modeling endeavors (Mikkelson et al., 2013).

In addition, as the slope angle increases, the saturation decreases. This is due to the fact that more water is being removed from the system in the form of runoff rather than infiltrating into the subsurface. Since the surface processes are driving the differences between the Green and Grey Phases of beetle mortality, with less water in the system these differences are also smaller. This means there is a distinct muting of the MPB signal with an increase in slope (Mikkelson et al., 2013), contradicting the increased risk of slope failure on steeper slopes.

4.3 Sensitivity Analysis of Factor of Safety Calculations

Overall, there was a decrease in the Factor of Safety as the hillslope went from Green to Grey Phase. This change was not significant relative to the changes related to different slopes and soil types (as displayed in Figure 3.6). As the slope angle increased, the Factor of Safety decreased, as expected. However, as the angle of the slope increased, there was less variation in the Factor of Safety between different soil types. This is directly controlled by the soil properties such as unit weight, internal angle of friction, cohesion, and hydraulic conductivity. As the slope angle increased, the soil properties had less influence on the Factor of Safety, reflecting the sensitivity to the slope geometries.

Table 3.1 describes the average change in Factor of Safety for the entire hillslope. The largest differences occurred at the lowest slope angles, which contained the largest differences in saturation. This means that the change in Factor of Safety, for the land cover change scenarios, is
driven by the modeled differences in saturation (rather than other parameter changes such as cohesion). In addition, the water table height in the gravel did not change much, due to the soil parameters such as high hydraulic conductivity. The water drained quickly through the soil displaying no difference in water table height from Green Phase to Grey Phase. Therefore, the overall differences in Factor of Safety from the Grey Phase and the Green Phase were an order of magnitude smaller than the other soils tested.

The response of the Factor of Safety to peak snowmelt compared to a large storm is different (for precipitation and SWE data see Appendix C). Overall, the Factor of Safety is highly sensitive to changes in saturation. Saturation is directly influenced from the snow water equivalent (SWE) and precipitation depending on the time of year. Since the Factor of Safety changes inversely with changes in saturation, with snowmelt and large rain events the Factor of Safety decreases. The peak saturation occurs due to peak snowmelt in mid-June. The response is the slow decline in the Factor of Safety throughout the fall and winter months to reach a minimum proceeding peak saturation. Throughout the summer, as the soil dries, there is a rapid increase in the Factor of Safety. At the beginning of September there is a large rain event that increases soil saturation from 0.25 to 0.30 throughout the domain. This change in mimicked by a rapid decline in the Factor of Safety by approximately 25%. The changes in the Factor of Safety are larger in the Grey Phase. The response to a rain event is a sharper decline in the Factor of Safety than due to snowmelt.

When comparing the toe of the slope to the head of the slope, the largest change in Factor of Safety is seen at the toe of the slope at low angles. As the slope angle increases, the difference
between the head and toe become smaller. Overall, for each soil type there is, on average, a 12% difference in the Factor of Safety between the head and toe of the slope. Although the Factor of Safety is overall highest at the toe of the slope, the change in Factor of Safety between the Green and Grey Phase is the most prominent.
CHAPTER 5

CONCLUSIONS

The forests tested in this experiment are very robust systems. Although the MPB infestation creates a huge land disturbance, the overall, dramatic impact of MPB mortality does not resonate at all scales (Bernsteinova et al., 2015; Beiderman et al., 2016). This is also the case with the changes in the Factor of Safety due to the investigation of changes in root tensile strength, integrated hydrologic modeling, and a sensitivity analysis of calculating the Factor of Safety. From a standpoint of Factor of Safety, the changes in Factor of Safety are small when looking at overall changes. From calculating the difference in tensile strength from Green to Grey Phase, the changes are on a scale of microPascals, which did not have an impact on the overall cohesion due to the differences in magnitude. On average, the difference between the Green and Grey Phase root tensile strength is 0.2μPa. However, the overall cohesion of the loamy sand, for example, was measured at 15 KPa (MDOT, 2013). The decay of the tree roots will likely also be counterbalanced by the increase of new vegetation. Hydrologic modeling displayed an increase in saturation as the hillslope went from the Green to Grey Phases of beetle mortality. These changes are focused primarily at the toe of the slope and along the water table within the soil above the crystalline bedrock. The changes in the Factor of Safety are a reflection of the changes in saturation; however, these changes are not enough to cause a distinguishable change in the Factor of Safety from Green to Grey Phase of beetle mortality. Soil properties played a role in the changes of the value of the Factor of Safety. These differences were more prevalent at lower slope angles. However, the difference in soil properties did not have an impact on the overall ratio of Green Phase and Grey Phase Factor of Safety. Although there are large
impacts in the surface processes as the MPB infests an area, when looking at slope stability MPB
does not create significant changes in the Factor of Safety.
REFERENCES


Association of Swiss Road and Traffic Engineers, Characteristics Coefficient of Soils, Swiss Standard SN 670 010b


Bearup, Lindsay A., Maxwell, Reed M., Clow, David W., McCray, John E., 2014. Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. Nature Climate Change.


Minnesota Department of Transportation, 2013. *Geotechnical engineering manual, geotechnical engineering section*.


Penn, Colin A., Maxwell, Reed M., Clow, David W., Bearup, Lindsay A., 2016. *Numerical experiments to explain multi-scale hydrological responses to mountain pine beetle tree mortality in a headwater basin*.


## APPENDIX A: LIMIT EQUILIBRIUM METHODS FOR CALCULATING FACTOR OF SAFETY

<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
<th>Description</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infinite Slope:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated</td>
<td>$FS = \frac{\tan\phi' + \frac{c' - \gamma(h_{w,0})\gamma}{\gamma}}{\tan\alpha}$ (Taylor, 1948; Godt, 2008)</td>
<td>Infinite-slope stability analysis is appropriate for translational landslides in which the failure depth is relatively small compared to the landslide length.</td>
<td>• Develop a grid to calculate the Factor of Safety at specific points throughout the slope (Godt, 2008)</td>
<td>• Ignores the contribution of roots along the perimeter of a landslide source volume (Schmidt, 2001) • Need to solve for Factor of Safety in the saturated and unsaturated zones (Godt, 2009) • There is a linear failure plane (Das, 2013)</td>
</tr>
<tr>
<td>Unsaturated</td>
<td>$X = \frac{g - \theta_r}{\theta_s - \theta_r}$ (Baum, 2008)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_s = \frac{g - \theta_r}{\theta_s - \theta_r}(u_s - u_w) = -S_s(u_s - u_w)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$FS = \frac{\tan\phi'}{\tan\alpha} + \frac{2\gamma \sin 2\alpha}{\theta_b \theta_b} \frac{\sigma_s}{\tan\alpha} + \cot\alpha \tan\phi'$ (Godt, 2009)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Finite Slope:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planar Failure Surface</td>
<td>$FS = \frac{CA + (W \cos \alpha - U)\tan\phi'}{W \sin \alpha}$ (Vallejo, 2011)</td>
<td>Applicable to rock slopes, a calculation that considers a planar failure surface.</td>
<td>• Simplest case of analysis (Vallejo, 2011)</td>
<td>• Inaccurate assumption if failure plane not a straight line • Applicable to primarily rock slopes • Rock slopes homogeneous (Vallejo, 2011)</td>
</tr>
<tr>
<td>Circular Failure Surface</td>
<td>$FS = \frac{f}{c_d} = \frac{c_u}{c_d}$</td>
<td>The failure plane is circular for undrained, homogeneous soil. The circular mass procedure assumes the soil above the failure plane moves as one unit (Das, 2013).</td>
<td>• The development of failure surfaces in not clearly defined (Taylor, 1948)</td>
<td>• Inaccurate assumption if failure plane not circular • Assumes normal stresses on the failure surface are concentrated at one point (Das, 2013). • Soil must be homogeneous and the water table horizontal (Das, 2013). • Undrained shear strength of the soil is assumed to be constant with depth (Das, 2013).</td>
</tr>
<tr>
<td></td>
<td>$c_u = b_{cr} \gamma m = \frac{W_1 l_1 - W_2 l_2}{r^2 \theta}$ (Das, 2013)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other Methods to Consider:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>Rocks: Wedge Failure, Buckling, Non-planar Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Method of Slices:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bishop</td>
<td>$FS = \frac{\sum_{n=1}^{n-1} (c' b_n + (W_{u_n} - u_{n-1} b_n) \tan \alpha)}{n_{m}} \frac{1}{m_n}$</td>
<td>Breaks the slope into multiple vertical, parallel slices and sums the driving and resisting forces within each slice (Vallejo, 2011).</td>
<td>• Commonly accepted as a calculation for Factor of Safety</td>
<td>• Assumes contact forces between each pair of slices are in equilibrium and therefore have no influence (Vallejo, 2011). • Inaccurate with high pore pressure and high friction cases (Das, 2013). • Best for solving for circular failure planes</td>
</tr>
<tr>
<td>Simplified Method of Slices</td>
<td>$FS = \frac{\sum_{n=1}^{n-1} W_n \sin \alpha n_{m}}{m_n}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$u_c = \cot \alpha \tan \phi'$ (Das, 2013)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other Methods to Consider:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordinary Method of Slices</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spencer’s Method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Janbu Method (non-circular failure)</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Parameters:

FS – Factor of Safety
W – weight
b – height
l – length
r – radius
α – slope angle
A – area
t – time
c’ – cohesion
u – pore pressure
Ψ – pressure head
φ – internal angle of friction
γ – (soil/water) unit weight
θ – (volumetric/saturated/residual) water content
APPENDIX B: SPATIAL STATISTIC ANALYSIS

INTRODUCTION

This research aims to identify the spatial correlation between slope stability and the locations of MPB tree mortality. The MPB tree mortality is hypothesized to slightly reduce the factor of safety at a hillslope scale. When the factor of safety drops below a value of 1, slope instability occurs through slope failures such as landslides. Through using the L-Cross Function, the interaction between the MPB infested area and area of landslides can be seen throughout different distances across the domain.

METHODS

DATA ACQUISITION

For this analysis, the data was collected to describe the MPB infestation, landslides and geology. The MPB infestation was collected from the U.S. Forest Service through an aerial survey (Colorado State Forest Service, 2015). The data was then ground checked in many locations. The MPB infestation data was cleaned using locations that experienced MPB (the data set contains other insect infestation), contained greater than 10 trees per acre impacted and are categorized as lodgepole pine or ponderosa pine forests. The landslide data was compiled from multiple maps digitized by the Colorado Geologic Survey. The locations where the landslide occurred pre-MPB infestations were removed (before 1994). The geologic map was collected from the web of soil survey from the USDA.
SPATIAL METHODS

DEFINING THE DOMAIN

The landslide data was the limiting factor due to its lack on continuity of data across the state of Colorado and course resolution. Thus, the domain was established in locations where this data was most prevalent (along roads and within residential areas). The domain follows I-70 and I-40 where there is a high density of recorded landslides. All the data types were clipped to the domain in ArcGIS. The polygon data of landslides, MPB, and geology were converted into NAD UTM 13; therefore, are all on the same coordinate system. The polygons, now fitted to the domain and in the same coordinate system are displayed in Figure B.1. In order to test for spatial randomness and remove heterogeneity from the intensity, a sub-domain was established as forested landscape (defined by the NLCD land cover dataset). The polygons of MPB, landslides, and geology were then clipped again since the location of interest is within pine forested areas.

Figure B.1: Domain and MPB Infested Area, Geologic Map, and Landslide Area
The centroids of the polygons were calculated in R in order to gain marked point pattern data. This was characterized as marked point pattern data because the domain is continuous and the points are random (Hering, 2016). The use of marked point pattern data was used to answer the question of spatial interaction between MPB infested areas, landslides, and geology. The data was initially tested on geostatistical as a grid; however, the measurements are not continuous throughout the domain and are highly binned.

L-CROSS FUNCTION

The K-Cross function is commonly used to investigate the interaction among point pattern data. If the bivariate point pattern is stationary and homogeneous, then the K-Cross function is symmetric ($k_{ij} = k_{ji}$) (Hering, 2016). However, the MPB and Landslide data do not abide by the homogeneous assumption. The inhomogeneous K-Cross function was estimated from the following equation (Hering, 2016):

$$
\hat{R}_{inhom} = \frac{1}{|D|} E \left[ \sum_{s_i \in X \cap D} \sum_{s_j \in X(s_i)} \frac{I(||s_k - u_t|| \leq h)}{\lambda(s_i)\lambda(s_j)} \right] \quad (B.1)
$$

where:

- $s_k$ is the location of type $i$ intensity;
- $u_t$ is the location of type $j$ intensity;
- $h$ is the distance;
- $X$ is the set of all events $s_i$ and $s_j$;
- $D$ is the domain;
- $\lambda_i$ is the intensity of data type $i$; and
- $\lambda_j$ is the intensity of data type $j$.

The L-Cross function is a function that is related to the K-Cross function through the following relationship (Hering 2016):
The null hypothesis states that there is no interaction between points of type i and type j. Thus, under the null hypothesis, \( L_{ij} = h \). The confidence intervals are assigned to be within +/- 2.5 of \( L_{ij} = h \). In addition, if the intensity varies spatially then the confidence intervals will widen because of the additional uncertainty.

One assumption that needs to be made is that the data is inhomogeneous. Thus density plots of the MPB infested locations and landslide locations were plotted to see if this assumption held true (Figure B.2). The distribution of points across the domain displays a varying intensity.

![MPB Intensity and Landslide Intensity](image)

**Figure B.2**: The kernel smoothed intensity plots of MPB infested area and landslides using the Diggle Bandwidth. The intensity changes across the domain; thus the point pattern data is inhomogeneous.

RESULTS AND DISCUSSION

The comparison of the centroids of locations impacted by the MPB and the centroids of landslides were investigated for interaction through using the L-Cross Function in R (Figure B.3)
(Baddeley & Turner). The plot displays the theoretical plot following complete spatial randomness (CSR), the observed interaction between the MPB and landslides, and the simulation envelope. The observed interaction between the MPB infested area and landslides were plotted outside of the simulation envelope for the majority of the distances across the domain. This means that there is significant evidence to reject the null hypothesis of that there is no interaction between the centroids of the MPB infested area and landslide area. The observations plotted below the theoretical plot following CSR, meaning that there is inhibition of points.

**Figure B.3:** Comparing centroids of the MPB impacted area and landslides using L-Cross Function. There is significant evidence to reject the null hypothesis due to inhibition at high distances across the domain.
CONCLUSIONS

The purpose of this study is to explore the spatial correlation of the MPB infestation on slope stability. Using the inhomogeneous L-Cross function, the null hypothesis was tested of there is no interaction between the landslides and the MPB. There was evidence to reject the null hypothesis due to the fact there was inhibition at distances greater than 4000m within the domain. Additional research could be conducted in order to try to explain the reason why there is interaction between the MPB impacted area and landslide locations. This could include further research both geostatically and point pattern data methods.

REFERENCES

Baddeley, A., Turner, R., Multitype L-function (cross-type). R Documentation.


APPENDIX C: MODEL PRECIPITATION AND SWE,

**Figure C.1:** Displays precipitation throughout the year for the hillslope

**Figure C.2:** Displays total SWE throughout the year for the hillslope.