Significance of tree root decomposition for shallow landslides

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\textbf{Abstract}

Tree-root systems can prevent shallow landslides. In layers permeated by roots, the soil shows greater stability as roots are able to absorb forces. When protective forests die off extensively as a consequence of a bark beetle outbreak or of another disturbance (e.g. storms or fires), their protective power on the slope stability decreases with the decomposition of the roots of the dead trees. By determining the relation between the tensile strength of roots and the tree’s time of death, the decrease in stability as a consequence of root decomposition can be estimated. To this end, we measured the tensile strength of roots from: i) freshly felled, living spruces (\textit{Picea abies}), ii) spruces felled eight years previously, and iii) spruces that had died 10 and 12 years previously in a bark beetle outbreak. Tensile strength decreased continuously with the number of years after death. The results of this study show that within 15 to 20 years of tree death, the root system of protection forests loses most of its soil-stabilising function. It can be assumed that, particularly at high altitudes, this period of time is not long enough for new generations of trees to have grown enough to have the same stabilising effect on the soil.

Keywords: shallow landslides, root tensile strength, erosion, protection forests, slope stability, tree mortality

\section{1 Introduction}

A stable and continuous vegetation, which is adapted to the local environment, has a positive effect on slope stability (for review, see Frehner \textit{et al.} 2005 and Reubens \textit{et al.} 2007). Tree-root systems enhance the shearing strength of the soil, enabling it to resist landslides and erosion (O’Loughlin 1974; Ziemer 1981; Watson and O’Loughlin 1985; Selby 1993; Rickli 2001; Simon and Collison 2002; Frei \textit{et al.} 2003). Through interception, evapotranspiration and enhancing soil permeability, forests also improve the hydrological characteristics of the soil (Ziemer 1981; Rickli 2001; Frehner \textit{et al.} 2005).

The positive effect of roots on soil stability depends both on the tensile strength of the individual roots (Fig. 1) and on the spatial distribution of the root mass in the soil (Simon and Collison 2002). The roots in the soil react variably to loads, depending on their diameter and on the soil material. They are stretched in a direction parallel to the load, absorbing tension loads (Waldron and Dakessian 1981; Schmidt \textit{et al.} 2001; Fournier \textit{et al.} 2006). This phenomenon may be compared to anchoring being tested for tensile strength in geotechnics (SN 505 267 2003).
When protection forests die off on a large scale as a consequence of disturbances (bark beetle outbreaks, storms, wildfires), the first protective function to be affected is the positive effect of trees on soil hydrology through evapotranspiration and interception (SELBY 1993). Once trees have died, their root system starts to decompose, eventually causing gaps in the interlocking root system of neighbouring individual trees (Fig. 1) (BURROUGHS and THOMAS 1977). It may be assumed that the positive effect on slope stability of deceased tree roots decreases with time, leading to an increased risk of landslides (ZIEMER 1981; RICKLI et al. 2002; SIDLE et al. 2005).

Detailed studies of rotting processes in tree roots and their effects on the strength of the roots have so far been carried out mainly in North America, New Zealand and Asia (O’LOUGHLIN and WATSON 1979; ZIEMER 1981; EKANAYAKE et al. 1997; WATSON et al. 1997; WATSON et al. 1999), following an increased incidence of shallow landslides after deforestation. In Alaska, a 20 to 25 % reduction in root strength was measured in the roots of Hemlock (Tsuga heterophylla [Raf.] Sarg.) and Sitka spruce (Picea sitchensis [Bong.] Carr.) only three years after the death of the trees (ZIEMER 1978; ZIEMER 1981). A 3.8-fold increase in the frequency of landslides was observed after large-scale decline of yellow cedars (Chamaecyparis nootkatensis [D.Don] Spach) (JOHNSON and WILCOCK 2002).

In Europe, the root strength of living trees has been studied (BISCHETTI et al. 2005), but no data regarding the decrease in root tensile strength after the dying off or cutting down of trees seem to be available. We therefore tested the tensile strength of Norway spruce roots from decomposing trees in Swiss mountain forests. In order to quantify how the effect of the root systems of dead trees or stumps on soil stability decreases with time, the tensile strength of root segments was measured. For this purpose roots were measured 8 to 12 years after tree death and compared with living ones (AMMANN 2006; AMMANN 2007).
2 Material and methodology

2.1 Study region

In the years 1992–97, a severe outbreak of bark beetles (*Ips typographus*) caused extensive die-off (approx. 100 ha) among the spruces of the Gandberg (Schwanden GL, Switzerland) mountain forest (Fig. 2). The trees in the damaged area have not been harvested, and, already five to ten years after death, started to snap a few meters above ground, leaving snags of various lengths in an upright position (stumps). These snags serve as props for dead trees lying crosswise on the slope.

The Gandberg area has a cool, humid climate. Based on the precipitation data from two weather stations within a distance of approximately 10 km (Elm and Braunwald), mean precipitation is estimated to be between 1600 and 2000 mm/year. Geologically Gandberg belongs to Verrucano of the Helvetic nappes (SPICHER 1980). The silicate-rich original material weathers to acid and fresh brown top soils with weak podsolisation (ROTH 1996). At our study sites, however no podsolisation was observed. For detail information on the selected material, see Table 1.

Fig. 2. The Gandbergwald Nature-Sanctuary (Photograph J. Walcher 1997). View from the opposite slope of the Western part of the Gandberg dead forest area. Up to an altitude of about 1200 m a.s.l. the spruces affected were cut and removed in order to prevent an increase in the bark beetle outbreak. In the area above that level, no felling took place and a large area with dead Norway spruces was left standing.

2.2 Test material

The roots were carefully dug up by hand and samples were taken. The spruce roots were identified morphologically. When doubts arose, the collected roots were traced back to a main root that could be identified unequivocally. The root pieces were selected to have a minimum length of 10 cm and a diameter of 5–20 mm under bark. Vertical or slanting roots were dug out to a depth of 1.0 m (KUTSCHERA and LICHTENEGGER 2002). No roots were taken from the top soil (0–30 cm). In each sampling site, roots were dug out on at least three, and at most five different spots. These spots within the homogeneous sampling site were located at a distance of at least five meters from one another to ensure that roots were obtained from different trees. The various test series are described in Table 1.
Table 1. Materials used in the four test series.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Category</th>
<th>Altitude</th>
<th>Time since death</th>
<th>Cause of death</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (ts₁)</td>
<td>Schwanden, recently harvested, living spruces</td>
<td>650 m a.s.l.</td>
<td>0 years</td>
<td>regular felling</td>
</tr>
<tr>
<td>2 (ts₂)</td>
<td>Schwanden, regular felling</td>
<td>900 m a.s.l.</td>
<td>8 years</td>
<td>regular felling</td>
</tr>
<tr>
<td>3 (ts₃)</td>
<td>Gandberg, montane zone</td>
<td>1250 m a.s.l.</td>
<td>10 years</td>
<td>bark beetles</td>
</tr>
<tr>
<td>4 (ts₄)</td>
<td>Gandberg, subalpine zone</td>
<td>1600 m a.s.l.</td>
<td>12 years</td>
<td>bark beetles</td>
</tr>
</tbody>
</table>

2.3 Tensile strength measurements

The root tensile strength was measured in the laboratory on a general test machine (MICRO 500/50kN-AX, Type ETM-50kN, Walter + Bai AG, Löhningen, CH). A major challenge was to mount roots of varying diameters and degrees of decomposition in the test machine so as to avoid premature failure. After preliminary tests, it was decided to reinforce the root terminals with a synthetic resin according to a method proposed by NILAWERA and NUTALA YA (1999). The root terminals were cast in resin cubes without bark (Fig. 3). This method enabled a clean transfer of force from the clamping devices to the root without slipping or damage. The samples were charged until fracture point with a constant feeding speed of 1 mm/min. Thus the roots were tested with mean strain rates of approximately $2.5 \times 10^{-4}$ s⁻¹, which amounts to testing under almost static conditions (Hertzberg 1989; Speck and Spatz 2003).

Before the test, the diameter without bark halfway along each root segment was measured (Fig. 3). Immediately following the test, the oven-dry density $\rho_{\text{dry}}$ and water content $u_{\text{root}}$ of the root material were measured. Subsequently, the specific fracture morphology was classified as one of four fracture types (BODIG and JAYNE 1982) (Fig. 4).

Fig. 3. Prepared root samples and measuring. To the left: root terminals cast in synthetic resin. Tensile force on roots was measured in x-direction. To the right: root between clamping jaws before tension test. 1: Wedge tensioner, lower part; 2: Wedge tensioner, upper part; 3: Vice clamps; $d_0$ = diameter without bark; $L_0$ : Length before test.
2.4 Analysis

The results of the root tensile tests were used first to calculate the tensile strength at the moment of maximal tensile force applied (point U in Fig. 5). Tensile strength $\sigma_{ult}$ [N/mm²] is calculated as shown in Equation 1 by dividing the maximal tension force $F_{ult}$ [N] by the initial cross-sectional area of the roots $A_0$ [mm²] (DIN 52188 1979; GIECK 1995).

$$\sigma_{ult} = \frac{F_{ult}}{A_0}$$

Fig. 5. Root tension test: Typical force-elongation diagram. b: near-linear elastic range; U: primary fracture point (maximal tensile force $F_{ult}$ is reached); T: complete fracture point; $\Delta F_{el}$: force difference in a near-linear elastic range; $\Delta L$: elongation; $\Delta L_{el}$: elongation in a near-linear elastic range (with $F_{el}$ applied); $\Delta L_{ult}$: elongation at maximal force ($F_{ult}$); $\Delta L_{frac}$: elongation at complete fracture.
Next, for each root in the force-elongation diagram, a linear elastic range (Fig. 5) was defined and the modulus of elasticity $E_{\text{root}}$ [N/mm^2] computed according to Equation 2 (GIECK 1995).

$$E_{\text{root}} = \frac{\Delta F_{\text{el}} \cdot L_0}{A_0 \cdot \Delta L_{\text{el}}}$$  \hspace{1cm} [2]

where $\Delta F_{\text{el}}$ is the force difference in the near-linear elastic range [N], $L_0$ the original length [mm], $A_0$ the nominal diameter before test [mm^2], and $\Delta L_{\text{el}}$ the elongation in the near-linear elastic range [mm].

Finally, the strain energy produced by the root during the test until the primary fracture point $U_{\text{ult}}$ [J] was calculated and so was the strain energy until the complete fracture point $U_{\text{frac}}$ [J] (Fig. 5). The area under the curve in the force/difference of length diagram (Fig 5) corresponds to the strain energy (SPECK and SPATZ 2003). This result can be derived from the root’s tensile strength $F$ [N] and change in length $\Delta L$ [mm]. Strain energies $U_{\text{ult}}$ (Equation 3) are calculated until maximal force is reached, and strain energies $U_{\text{frac}}$ (Equation 3) until complete fracture (points U and T in Fig. 5).

$$U_{\text{ult}} = \int_0^{\Delta L_{\text{ult}}} F \, d\Delta L \; ; \; \; \; U_{\text{frac}} = \int_0^{\Delta L_{\text{frac}}} F \, d\Delta L$$  \hspace{1cm} [3]

### 2.5 Statistics

Due to a few missing values, the statistical analysis was restricted to 109 of the totally 112 processed samples. The calculations were performed with the software packages R 2.5.0 (R Development Core Team 2007). Linear regression models were calculated for the following response variables ($Y$): tensile strength ($\sigma_{\text{ult}}$), strain energy until primary breaking ($U_{\text{ult}}$), strain energy until complete fracture ($U_{\text{frac}}$) and modulus of elasticity ($E_{\text{root}}$); all log-transformed to meet the assumptions that the error terms follow identical and independent normal distributions. The explanatory variables were: wood density ($\rho_{\text{dry}}$), root diameter ($d_0$), water content ($u_{\text{root}}$) and the two four-levelled factors test series ($t_s$, Table 1) and fracture type ($i_{\text{frac}}$, Fig. 4). Treatment contrasts were applied for coding the factors with the baseline levels specified by test series 1 and the splintering fracture type. The Tukey’s all-pair comparisons for treatment differences were calculated for the factors remaining in the selected models (HOTHORN et al. 2008). The appropriate models were identified starting from the complete default model including all independent variables (Equation 4), applying a stepwise backward selection procedure based on the AIC criterion (VENABLES and RIPLEY 2002).

$$\log(Y) \sim \rho_{\text{dry}} + d_0 + u_{\text{root}} + i_{\text{frac}} + t_s$$  \hspace{1cm} [4]

Residual analysis was performed to check the compliance of the assumptions required and the fit of the selected models. For that purpose residuals against fitted values (Tukey-Anscombe plot) and against leverages (hat matrix) were analysed as well as the quantil-quantil plots (Q-Q plots, normal plots). Additionally, the factors test series ($t_s$) and fracture type ($i_{\text{frac}}$) were analysed separately with pair-wise Wilcoxon rank sum tests in relation to
each of the four response variables used in the linear regression analyses. Corrections for multiple testing were performed according to HOMMEL (1988). The codes referred to for illustrating significant differences (p-values) are: $0 \leq *** \leq 0.001$, $0.001 < ** \leq 0.01$, $0.01 < * \leq 0.05$, $0.05 < \bullet \leq 0.1$.

3 Results

3.1 Root segments tested

A total of 158 root segments were cast into resin. Out of these, 46 segments (29%) could not be tested as they broke during test preparations or fractured within their resin packing during the test. A total of 112 (71%) roots were examined in four test series (Table 2). The roots tested had diameters ranging from 2.78 to 10.40 mm. Statistical analysis was performed on 109 of the totally 112 investigated samples.

Table 2. Properties and parameters of roots in all test series (see also Table 1). The mean values are given with their standard deviations in brackets.

<table>
<thead>
<tr>
<th>Test series</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Number of tests [years]</td>
<td>33</td>
<td>21</td>
<td>46</td>
<td>12</td>
</tr>
<tr>
<td>Time since death</td>
<td>0</td>
<td>8</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>$d_0$ Nominal diameter [mm]</td>
<td>5.41</td>
<td>5.03</td>
<td>7.08</td>
<td>5.65</td>
</tr>
<tr>
<td></td>
<td>(±1.47)</td>
<td>(±1.69)</td>
<td>(±1.67)</td>
<td>(±1.93)</td>
</tr>
<tr>
<td>$L_0$ Original length [mm]</td>
<td>69.90</td>
<td>73.36</td>
<td>76.06</td>
<td>65.85</td>
</tr>
<tr>
<td></td>
<td>(±4.49)</td>
<td>(±7.94)</td>
<td>(±9.78)</td>
<td>(±8.09)</td>
</tr>
<tr>
<td>$\rho_{\text{dry}}$ Wood density (oven-dry) [kg/dm$^3$]</td>
<td>0.479</td>
<td>0.496</td>
<td>0.480</td>
<td>0.513</td>
</tr>
<tr>
<td></td>
<td>(±0.078)</td>
<td>(±0.099)</td>
<td>(±0.107)</td>
<td>(±0.150)</td>
</tr>
<tr>
<td>$u_{\text{root}}$ Wood water content [%]</td>
<td>11.69</td>
<td>8.03</td>
<td>8.53</td>
<td>15.33</td>
</tr>
<tr>
<td></td>
<td>(±1.00)</td>
<td>(±1.51)</td>
<td>(±1.09)</td>
<td>(±12.07)</td>
</tr>
<tr>
<td>$F_{\text{ult}}$ Max. force [N]</td>
<td>479.50</td>
<td>322.51</td>
<td>553.97</td>
<td>180.44</td>
</tr>
<tr>
<td></td>
<td>(±333.08)</td>
<td>(±303.57)</td>
<td>(±394.21)</td>
<td>(±90.46)</td>
</tr>
<tr>
<td>$\sigma_{\text{ult}}$ Tensile strength [N/mm$^2$]</td>
<td>18.31</td>
<td>13.30</td>
<td>13.03</td>
<td>7.89</td>
</tr>
<tr>
<td></td>
<td>(±7.00)</td>
<td>(±6.30)</td>
<td>(±7.31)</td>
<td>(±3.84)</td>
</tr>
<tr>
<td>$\Delta L_{\text{ult}}$ Elongation at maximal force [mm]</td>
<td>5.39</td>
<td>2.05</td>
<td>1.12</td>
<td>3.33</td>
</tr>
<tr>
<td></td>
<td>(±3.09)</td>
<td>(±1.77)</td>
<td>(±0.85)</td>
<td>(±3.03)</td>
</tr>
<tr>
<td>$U_{\text{ult}}$ Strain energy until primary fracture [J]</td>
<td>1.436</td>
<td>0.281</td>
<td>0.360</td>
<td>0.454</td>
</tr>
<tr>
<td></td>
<td>(±1.174)</td>
<td>(±0.203)</td>
<td>(±0.316)</td>
<td>(±0.625)</td>
</tr>
<tr>
<td>$U_{\text{frac}}$ Strain energy until complete fracture [J]</td>
<td>1.824</td>
<td>0.359</td>
<td>0.443</td>
<td>0.713</td>
</tr>
<tr>
<td></td>
<td>(±1.691)</td>
<td>(±0.280)</td>
<td>(±0.404)</td>
<td>(±0.793)</td>
</tr>
<tr>
<td>$E_{\text{root}}$ Modulus of elasticity [N/mm$^2$]</td>
<td>527.91</td>
<td>872.76</td>
<td>1394.05</td>
<td>432.80</td>
</tr>
<tr>
<td></td>
<td>(±419.47)</td>
<td>(±642.23)</td>
<td>(±791.27)</td>
<td>(±228.99)</td>
</tr>
</tbody>
</table>

3.2 Tensile strength

Tensile strength ($\sigma_{\text{ult}}$) is significantly affected by the factor test series. All combinations of two of the four levelled factor test series ($t_i$) differ significantly, except that between the test series 2 and 3. Furthermore, it was observed that tensile strength significantly decreases with increasing factor level (test series, Fig. 6) except between series 2 and 3. This reduction in
tensile strength may also be associated to increasing time since root death or to the altitude (m a.s.l.) of the root sampling locations which are both positively correlated with the four test series (Table 1). No significant results were obtained from the pairwise Wilcoxon rank sum tests of the factor fracture type ($i_{frac}$) related to tensile strength.

The model selection process for the response variable tensile strength ($\sigma_{ult}$) finally resulted in the linear regression model (Equation 5) with the explanatory variables: wood density ($\rho_{dry}$), root diameter ($d_0$), and test series ($t_s$).

$$\log(\sigma_{ult}) \sim \rho_{dry} + d_0 + t_s$$

[5]

This model explains 29% of the deviance (Table 3). The numeric variable wood density ($\rho_{dry}$) and the factor test series ($t_s$) influence the log-transformed tensile strength significantly, the former far stronger than the latter, and the root diameter ($d_0$) only by trend. All levels of the factor test series significantly contrast with the baseline level, represented by test series 1. Furthermore, a steady decrease related to the baseline level was detected with increasing level of the test series. The Tukey’s all-pair comparisons revealed further significant differences between the combinations of the test series 2 and 4, as well as between 3 and 4.
Table 3. List of summary statistics of the fitted linear model with the response variable tensile strength 
\( \log(\sigma_{ult}) \sim \rho_{dry} + d_0 + t_s \).

| Coefficients                      | Estimate | Std. Error | t value | Pr(>|t|) |
|-----------------------------------|----------|------------|---------|----------|
| (Intercept)                       | 0.78399  | 0.13905    | 5.638   | 1.51 e-07 *** |
| \( \rho_{dry} \): wood density    | 0.65797  | 0.21694    | 3.033   | 0.00306 **  |
| \( d_0 \): root diameter         | 0.02399  | 0.01347    | 1.782   | 0.07774  • |
| \( t_{s2} \): test series 2      | -0.14929 | 0.06337    | -2.356  | 0.02037 *  |
| \( t_{s3} \): test series 3      | -0.22521 | 0.05720    | -3.937  | 0.00015 ***|
| \( t_{s4} \): test series 4      | -0.43798 | 0.07907    | -5.539  | 2.34e-07 ***|

Residual standard error: 0.226 on 103 degrees of freedom (DF)
Multiple R\(^2\): 0.2862
Adjusted R\(^2\): 0.2515
F-statistic: 8.258 on 5 and 103 DF
p-value: 1.366 e-06

3.3 Strain energy

Related to both strain energy until primary breaking (\( U_{ult} \)) and strain energy until complete 
fracture (\( U_{frac} \)), the test series 1 differs significantly from all other series except for the 
comparison between test series 1 and 4 related to \( U_{frac} \). All other comparisons of the 
combinations of two are not significant. Likewise, no significant results were obtained for the 
factor fracture type (\( i_{frac} \)) related to both \( U_{ult} \) and \( U_{frac} \).

The selected linear regression models (Equation 6) of the variables strain energy until 
primary breaking (\( U_{ult} \)) and strain energy until complete fracture (\( U_{frac} \)) constitute of the 
explanatory variables: wood density (\( \rho_{dry} \)), root diameter (\( d_0 \)), water content (\( u_{root} \)), and the 
factor test series (\( t_s \)).

\[
\log(U_i) \sim \rho_{dry} + d_0 + u_{root} + t_s \quad i: U_{ult}, U_{frac}
\]

The linear models for \( \log(U_{ult}) \) and \( \log(U_{frac}) \) explain 57 % and 56 % of the deviance, 
respectively (Table 4, 5). Both response variables are significantly affected by all considered 
explaining variables. The effect of wood density on (\( \log(U_{ult}) \)) and (\( \log(U_{frac}) \)) is ten and 
eight times higher, respectively than the effect of root diameter. The influence of root diameter 
on its part on \( \log(U_{ult}) \) and \( \log(U_{frac}) \) is five and eight times higher, respectively than that of 
the water content of the roots. All levels of the factor test series significantly contrast with 
the baseline level (test series 1) and, in the case of the strain energy until primary breaking, 
steadily decrease from the baseline level with increasing level of test series. For the strain 
energy until complete fracture, however, the decrease of the level test series 4 is less than 
that of the level test series 3. The all-pair comparisons based on Tukey contrasts revealed an 
additional significant difference between test series 2 and 3 related to the strain energy until 
complete fracture.
Table 4. List of summary statistics of the fitted linear model with the response variable strain energy until primary breaking \((\log(U_{ult}) \sim \rho_{dry} + d_0 + u_{root} + t_s)\).

| Coefficients | Estimate | Std. Error | t value | Pr(>|t|) |
|--------------|----------|------------|---------|----------|
| (Intercept)  | -1.76020 | 0.27250    | -6.460  | 3.63e-09 *** |
| \(\rho_{dry}\) : wood density | 1.36003 | 0.37218    | 3.654   | 0.000409 *** |
| \(d_0\) : root diameter | 0.14653 | 0.02251    | 6.509   | 2.87e-09 *** |
| \(u_{root}\) : water content | 0.02721 | 0.00973    | 2.795   | 0.006193 ** |
| \(t_{s2}\) : test series 2 | -0.56358 | 0.11034    | -5.108  | 1.52e-06 *** |
| \(t_{s3}\) : test series 3 | -0.82379 | 0.10118    | -8.142  | 1.01e-12 *** |
| \(t_{s4}\) : test series 4 | -0.94399 | 0.13928    | -6.778  | 8.06e-10 *** |

Residual standard error: 0.3754 on 102 degrees of freedom (DF)
Multiple R\(^2\): 0.5697
Adjusted R\(^2\): 0.5444
F-statistic: 22.51 on 6 and 102 DF p-value: < 2.2 e-16

Table 5. List of summary statistics of the fitted linear model with the response variable strain energy until complete fracture \((\log(U_{frac}) \sim \rho_{dry} + d_0 + u_{root} + t_s)\).

| Coefficients | Estimate | Std. Error | t value | Pr(>|t|) |
|--------------|----------|------------|---------|----------|
| (Intercept)  | -1.69767 | 0.28362    | -5.986  | 3.24e-08 *** |
| \(\rho_{dry}\) : wood density | 1.26718 | 0.38737    | 3.271   | 0.00146 ** |
| \(d_0\) : root diameter | 0.16967 | 0.02343    | 7.241   | 8.62 e-11 *** |
| \(u_{root}\) : water content | 0.02175 | 0.01013    | 2.147   | 0.03415 * |
| \(t_{s2}\) : test series 2 | -0.57517 | 0.11485    | -5.008  | 2.31 e-06 *** |
| \(t_{s3}\) : test series 3 | -0.89545 | 0.10531    | -8.503  | 1.64 e-13 *** |
| \(t_{s4}\) : test series 4 | -0.72793 | 0.14496    | -5.022  | 2.19 e-06 *** |

Residual standard error: 0.3907 on 102 degrees of freedom (DF)
Multiple R\(^2\): 0.5623
Adjusted R\(^2\): 0.5365
F-statistic: 21.84 on 6 and 102 DF p-value: < 2.254 e-16

3.4 Modulus of elasticity

Related to the modulus of elasticity \((E_{root})\) the test series 3 differs significantly from the others. The remaining comparisons of the combinations of two are not significant. Additionally, a single significant difference was observed for the factor fracture type related to the modulus of elasticity, namely between the types “snap or separation fracture” and “clean-cut shear fracture”.

The final linear regression model (Equation 7) for the modulus of elasticity \((E_{root})\) explains 36 % of the deviance and includes the numeric variable root diameter \((d_0)\), and the factor test series \((t_s)\). Both significantly influence the log-transformed response variable (Table 6).

\[
\log(E_{root}) \sim d_0 + t_s \] [7]
The levels test series 2 and test series 3 are significantly higher than the baseline level (test series 1). However, the corresponding decrease of the level test series 4 is not significant. The Tukey’s all-pair comparisons revealed an additional significant difference between the levels test series 3 and 4.

Table 6. List of summary statistics of the fitted linear model with the response variable modulus of elasticity \((\log(E_{root}) \sim d_0 + t_s)\).

| Coefficients: | Estimate | Std. Error | t value | Pr(>|t|) |
|---------------|----------|------------|---------|----------|
| (Intercept)   | 2.33254  | 0.11643    | 20.034  | <2.0e-16 *** |
| \(d_0\) : root diameter | 0.05117  | 0.01892    | 2.705   | 0.00799 **  |
| \(t_{s2}\) : test series 2 | 0.22256  | 0.08948    | 2.487   | 0.01446 *   |
| \(t_{s3}\) : test series 3 | 0.37505  | 0.08070    | 4.648   | 9.89e-06 *** |
| \(t_{s4}\) : test series 4 | -0.07738 | 0.11138    | -0.695  | 0.48876      |

Residual standard error: 0.3195 on 104 degrees of freedom (DF)
Multiple R-Squared: 0.3558
Adjusted R-Squared: 0.331
F-statistic: 14.36 on 4 and 104 DF p-value: 2.286e-09

4 Discussion

4.1 Data comparison

The tensile strength of tree roots decreases after the tree dies. In our study, we found the tensile strength of the decaying roots of spruces that had died about 8 years previously was only approximately 60% of the original strength (Fig. 7). No relevant change in tensile strength was observed between roots of trees felled 8 years previously and roots of trees that had died off 10 years previously. Yet, the root-strength of trees died 12 years previously had declined to approximately 30% of the original value. Strain energy already declined significantly in the first years after tree death. Partly decomposed roots (dead for 8 to 12 years) produced only 22% of the original strain energy until complete fracture \(U_{frac}\) and 11% of the original strain energy until primary breaking \(U_{ult}\), respectively. However, no continuous reduction in strain energy with time could be found. This may be because the roots’ water contents varied in spite of the identical preparation of the root segments (Table 2). The pronounced decrease in strain energy over the first years (Fig. 7) is probably due to a corresponding state of brittleness in the roots. After this period, further root decay seems to render the roots more susceptible to yielding. Accordingly no further decrease in strain energy was recorded.

Comparisons with other studies have to be made with caution, as differences in the selection of test material (diameter, curvature), in the storage of the roots until testing (water content) and in the test procedures may strongly influence the values of tensile strength. The tensile strength values for the roots of freshly felled, living spruces measured in this study (18.31 ± 7.00 N/mm²) are considerably below the values (38.94 ± 83.79 N/mm²) reported by BISCHETTI et al. (2005) in spruce roots that were significantly thinner (1.78 ± 1.19 mm) than to the roots tested here (5.41 ± 1.47). However, our results fall within the range of the values (15 to 30 N/mm²) measured by GENET et al. (2005) in spruce roots with diameters between 4 and 5 mm.
By casting the root terminals in synthetic resin, we were able to obtain more evaluable test results (70%) than in studies with less accurate mounting. Genet et al. (2005) placed cork between the root and the clamping jaws, with about 30% of successful tests. Casting the root terminals in resin allowed the transmission of loads between the clamping jaws and the rigid resin block to take place without loss of force or slipping. It was thus possible to subsequently measure the strain energy, which can only be done if the changes in root length during the test are measured very exactly. Previous studies were not able to obtain data on the strain energy of roots because of the technologies and methods applied.

The modulus of elasticity of roots does not depend on their state of decay according to our study. Tests on pine roots (Pinus radiata) 3 to 30 months after cutting yielded similar results (O’Loughlin and Watson 1979).

### 4.2 Methodological considerations

Significant factors affecting a forest’s protection function against landslides include not only the tensile strength and strain energy of its trees’ roots, but also their root mass (Johnson and Wilcock 2002; Saklas and Sidle 2004). In our study we did not directly investigate how mass decreases with decomposition, but we assumed that loss of mass occurs proportionally to loss of strength (Ziemer 1981). On the steep slopes of our study site, Gandbergwald, the costs of representative sampling of root quantities according to known methods, e.g. uncovering roots using water under high pressure (Watson et al. 1995) or meticulous excavation of the complete root system (Watson and O’Loughlin 1985;
JOHNSON and WILCOCK 2002), would have been prohibitive. Data on root mass distribution in the soil, combined with tensile strength characteristics, would, however, be very useful to estimate the influence of roots on the shear strength of the soil and, consequently, on slope stability (ABE and ZIEMER 1991; SIDLE 1991; REUBENS et al. 2007).

4.3 Decomposing root systems and shallow landslides

The soil-bolstering function of the roots of dead trees declines as their strength decreases. If the vegetation is not replaced soon enough, erosion processes may be aggravated, with increased weathering and more water penetrating into the soil through the spaces created by the decayed roots. This, in turn, may trigger off shallow landslides (REUBENS et al. 2007). Consequently, after a large-scale tree die-off in mountain forests, a triggering event such as heavy rain or massive snow melting, can be a serious threat to slope stability (Fig. 8). This has been clearly demonstrated by RICKLI et al. (2002): In the wake of a thunderstorm in 1997 in Sachseln, Obwalden, substantially more landslides per km² were triggered off in forest stand destroyed by bark beetles or wind throw than in undisturbed parts of the forest.

Fig. 8. Shallow landslide in the catchment area of the Grossbach torrent near Einsiedeln (Switzerland) after the June 2007 thunderstorm. The lower part of the area had been blown down by hurricane Lothar (1999), the upper part was damaged by the subsequent bark beetle outbreak in the years 2000–2003. Shallow landslides occurred over the whole area as a consequence of the damage wrought by the bark beetles.
Similar research in North America confirms that the incidence of landslides in places where deforestation has taken place is higher than in areas where natural vegetation has been conserved (ZIEMER 1978; WU et al. 1979). Our own observations in the Grosser Runs near Einsiedeln after a thunderstorm on 20 June 2007 also confirm this. Many shallow landslides occurred in the catchment basin, which consists geologically mainly of landslide-prone Flysch, in areas damaged by hurricane Lothar in 1999 or by the subsequent bark beetle outbreaks (2000–2003). The thunderstorm occurred four to seven years after the spruce die-off caused by bark beetles and eight years after Lothar. It seems that the decomposed roots of the deceased trees were no longer able to maintain soil stability, and the newly-sprouting spruces and pioneer flora were not yet able to compensate for the stability lost.

On the basis of our data, we can conclude that soil stability depending on root systems will enter a critical phase some years after large-scale die-off in a pure spruce forest, caused either naturally or by human intervention. It can be assumed that this time span depends on the decomposition rate of the roots which in turn is a function of site parameters such as altitude (climate) and soil water regime. Important factors for evaluating the risk of landslides or erosion after tree death are not only the length of decomposition but also the gradient of the slope and the soil material’s susceptibility to landslides. Slopes with a gradient steeper than the angle of internal friction of the material in question are more susceptible to landsliding as a consequence of the diminished protective function of the vegetation (BÖLL 1983; FREHNER et al. 2005). That is, such slopes may remain stable if they are covered with intact protective vegetation, but they will become unstable if the conditions of the forest deteriorate or after a wooded area dies off (SELBY 1993).

Acknowledgements
We thank Frank Graf (WSL) for stimulating discussions and suggestions, Norina Bürkler (WSL) for excellent technical assistance and Marco Pautasso (ETH Zurich) for valuable comments on the manuscript draft. We are very grateful to the Velux Stiftung for financial support (project nr. 66 Oek: “Protective function of deceased trees against natural hazards” and complementary project nr. 302: “Tension strength of roots”).

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Revised version accepted June 6, 2009