

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository:<https://orca.cardiff.ac.uk/id/eprint/94043/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Hales, Tristram and Miniati, C. F. 2017. Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability. *Earth Surface Processes and Landforms* 42 (5) , pp. 803-813. 10.1002/esp.4039

Publishers page: <http://dx.doi.org/10.1002/esp.4039>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability

Hales, T.C.¹, and Miniati, C.F.²

¹ School of Earth and Ocean Sciences, Cardiff University, halest@cf.ac.uk, Phone +44 29 208 74329, Fax +44 29 208 74326.

² USDA Forest Service, Southern Research Station, Coweeta Hydrologic Laboratory, Otto, NC

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/esp.4039

Abstract

In steep soil-mantled landscapes, the initiation of shallow landslides is strongly controlled by the distribution of vegetation, whose roots reinforce the soil. The magnitude of root reinforcement depends on the number, diameter distribution, orientation and the mechanical properties of roots that cross potential failure planes. Understanding how these properties vary in space and time in forests remains a significant challenge. Here we test the hypothesis that spatio-temporal variations in root reinforcement along a hillslope occur as a function of topographic soil moisture gradients. To test this hypothesis we compared root reinforcement measurements from relatively dry, divergent noses to relatively wet, convergent hollows in the southern Appalachian Mountains, North Carolina, USA. Our initial results showed that root reinforcement decreased in areas of higher soil moisture because the tensile strength of roots decreased. A post-hoc laboratory experiment further demonstrated that root tensile strength decreased as root moisture content increased. This effect is consistent with other experiments on stem woods showing that increased water content in the cell wall decreases tensile strength. Our experimental data demonstrated that roots can adjust to changes in the external root moisture conditions within hours, suggesting that root moisture content will change over the timescale of large storm events (hours-days). We assessed the effects of the dynamic changes in root tensile strength to the magnitude of apparent cohesion within the infinite slope stability model. Slopes can be considerably less stable when precipitation-driven increases in saturated soil depth both increase pore pressures and decrease root reinforcement.

Keywords

Root reinforcement, slope stability, root tensile strength, soil moisture

Introduction

Vegetation controls the spatial distribution and frequency of shallow landslide events through modifying the shear strength and hydrology of the soil (Benda and Dunne, 1997, Casadei and Dietrich, 2003, Crozier et al., 1990, Gabet and Dunne, 2002, Iida, 1999, Iida and Okunishi, 1983). Plants that have stronger roots, or more extensive root systems have fewer landslide initiations during storms (Gabet and Dunne, 2003). When landslides do occur in stronger and more extensively rooted vegetation, they are wider and of greater total volume than those associated with weaker-rooted systems (Casadei and Dietrich, 2003, Milledge et al., 2014). Characterising the magnitude of the shear strength provided by roots is challenging due to the complex nature of belowground biomass, even in monocultures and plantation-type stands, and the uncertain mechanics of the behaviour of root bundles in soil (Bourrier et al., 2013, Pollen and Simon, 2005, Schwarz et al., 2010, Waldron, 1977, Waldron and Dakessian, 1981, Wu et al., 1979). Despite advances in our ability to model the mechanical root behaviour in soils (Pollen and Simon, 2005, Schwarz et al., 2010), to observe root tensile strength distribution (Anderson et al., 1989, Bischetti et al., 2005, Coutts, 1983, Genet et al., 2005, Ghestem et al., 2013, Hathaway and Penny, 1975, O'Loughlin and Watson, 1979, O'Loughlin and Ziemer, 1982), and to observe and model the spatial distribution of root reinforcement at the stand level (Cohen et al., 2011, Genet et al., 2011, Hales et al., 2009, Roering et al., 2003, Sakals and Sidle, 2004), estimating root reinforcement at the hillslope-scale is still challenging. Here we investigate whether systematic changes in soil moisture content along a hillslope affects root reinforcement at a hillslope-scale.

Environmental factors, such as precipitation, temperature, soil structure and composition play an important role in governing the distribution of belowground biomass (Nicotra et al., 2002, Schenk and Jackson, 2005) and, by inference, root reinforcement. Key drivers known to affect belowground biomass distributions are these: (1) plant-available soil resources such as nutrients and soil moisture (e.g. Laio et al., 2006, Schenk and Jackson, 2002), (2) mechanical resistance of the soil (e.g. Stone and Kalisz, 1991), (3) age of

individual plants (e.g. Cairns et al., 1997), and (4) species (e.g. Ji et al., 2012). Coarse relationships between climate and rooting distributions in water-limited environments are linked to the role that roots play in extracting soil moisture for transpiration (Walter, 1973, Weltzin and McPherson, 1997). Ecohydrologic modelling methods calibrated to water limited environments demonstrate that rooting distributions vary as a function of soil moisture content, with greater root biomass allocated to areas of high soil moisture content (Laio et al., 2006, Sivandran and Bras, 2012, Sivandran and Bras, 2013). These ecohydrological approaches have been incorporated into slope stability analyses for water-limited environments (Preti et al., 2010, Tron et al., 2014). Ecohydrological modelling methods have also significantly improved regional estimates of landslide potential in humid catchments, however these models rely on empirical relationships between canopy height and belowground biomass to drive slope stability modelling rather than explicitly growing roots (Hwang et al., 2015). The role of soil moisture in governing root reinforcement in humid landscapes, where water is not a limiting resource, is not well understood, as are the mechanical relationships between root bundles and soil moisture conditions.

Systematic environmental controls on the mechanical properties of roots have been investigated by a few studies (Genet et al., 2011, Genet et al., 2005, Hales et al., 2013, Hales et al., 2009, Yang et al., 2016, Zhang et al., 2014). The strength of any root is dependent on the amount of vascular tissue (i.e., xylem) present (Hathaway and Penny, 1975). Root strength under tension increases with increasing amount of xylem, and hence root diameter (Abernethy and Rutherford, 2001, Hathaway and Penny, 1975, Schmidt et al., 2001, Waldron, 1977, Wu et al., 1979). Within the xylem, cellulose content has been identified as a main contributor to root strength (Genet et al., 2005, Hales et al., 2009, Zhang et al., 2014). Environmentally driven changes in the structure of roots, particularly the distribution or density of cellulose microfibrils, should affect any non-genetic variability in root mechanical properties. Air temperature, precipitation, and soil moisture content all contribute to measureable changes in the strength of stem wood, with drier conditions supporting stronger and denser wood; hence, these controls should also affect root strength where

roots have a similar vascular structure to wood (Genet et al., 2011, Hacke et al., 2001, Hales et al., 2009, Kretschmann, 1999, Winandy and Rowell, 2005). Changes in root structure with water content have been hypothesized as a mechanism explaining why roots collected on drier topographic noses have higher cellulose content than those collected in wetter hollows (Hales et al., 2009). Soil moisture also affects root reinforcement by affecting the frictional strength of the root-soil bond (Pollen, 2007) and thickening the shear zone (Fan and Su, 2009). Weaker root-soil bonds reduce the net reinforcement provided by roots in wetter soils (Pollen, 2007, Pollen-Bankhead and Simon, 2010). Taken as a whole, these results suggest that where systematic changes in temperature or moisture exist they will be associated with concomitant changes in root reinforcement.

Root reinforcement, defined here as the contribution of roots to the apparent cohesion of the soil, is a function of root distribution, root strength, and elasticity. This value represents the maximum additional shear strength provided by roots. Root reinforcement may vary systematically along hillslope hydrologic pathways. Trees growing on drier sites on a single hillslope have a greater proportion of roots at deeper depths (Hales et al., 2009). Root strength, like stem wood, may also be higher in drier locations because xylem is more structurally reinforced (e.g., greater cellulose content) (Hacke et al., 2001). The structural reinforcement of xylem reduces the potential for drought stress by cavitation, which causes a loss of hydraulic conductance in xylem tissue (Hacke et al., 2001). Our study seeks to understand whether the observations of differing rooting distributions and xylem strengths affect the potential for landslide triggering for different soil moisture conditions. We conducted a field study that measured changes in root distributions and strengths under different relative soil moisture conditions of topographic noses and hollows. We also conducted a post-hoc, controlled lab experiment to examine the relationship between root moisture and root strength, since the initial results of the field experiment suggested that this might be an important link. Finally, we investigated how changes in root reinforcement associated with soil moisture affect slope stability by calculating factor of safety for different

soil moisture scenarios and modelling root reinforcement at the hillslope scale during a storm event.

Methods

Study Sites

Our experimental field study was located in the Coweeta Hydrologic Laboratory in the southern Appalachian Mountains of North Carolina, USA (Swank and Crossley, 1988). Shallow landslides initiate in steep, convergent topography in the upper part of the Coweeta Hydrologic Laboratory (Hursh, 1941, Wooten et al., 2016). Our study sites were located within the upper part of the catchment, in a 144-ha watershed (Watershed 28) ranging from 900 to 1,500 m in elevation (Douglass and Swank, 1976). Watershed 28 has two main forest community types: Northern hardwood forest, of which *Betula lenta* L. is a dominant species, and cove hardwood forest, of which *Liriodendron tulipifera* L. is a dominant species (Bolstad et al., 1998, Day et al., 1988). Understory woody species were relatively sparse in our sites, suggesting that the tree roots were the major contributor to root reinforcement. The watershed was managed for multiple-use, where the cove hardwood forest was thinned in 1963–1964 to promote growth of several species, including *L. tulipifera*. The Northern hardwood areas were clearcut during the same time (Douglass and Swank, 1976). At the time of our study in July 2009, trees in the cove forest were *ca.* 85-yrs old, while those in the northern hardwood forest areas were *ca.* 45-yrs old.

We excavated 12 soil pits ($\sim 1 \text{ m}^3$), from two topographies (relatively dry, divergent noses and relatively wet, convergent hollows), and two tree species (*L. tulipifera*, *B. lenta*) in Watershed 28 (Fig. 1). Areas of convex (noses) or concave (hollows) topography were identified in the field, in stands of trees of the species of interest. Slope was measured in the field along the axis of the topographic feature using an inclinometer. Aspect, curvature, and contributing area were measured from the 6 m North Carolina State LiDAR dataset (www.ncfloodmaps.com). Each pit was manually excavated with a front face 80 cm downslope of the tree species of interest. Each pit had a planform area of 1 m^2 , a minimum

depth of 60 cm and a maximum of 120 cm. The topographies of our pit sites were similar (Table 1); however, our higher elevation *B. lenta* sites were steeper and more convergent. *B. lenta* sites were north facing while *L. tulipifera* sites were northeast facing. These slight differences in topography of our sites are reflective of the increasing steepness of the Nantahala and other mountains (e.g., Blue Ridge) of the area. Topographic metrics calculated from the LiDAR data show that aspects and slopes are indistinguishable for noses and hollows. Planform convexity and concavity, calculated at a scale of 18 m, had a similar magnitude for noses and hollows, i.e. noses were no more or less convex than the concavity of adjacent hollows.

We supplemented the field experiment with a controlled laboratory experiment to test the relationship between root moisture content and tensile strength. We collected roots from three common British plantation forest species (*Picea sitchensis* (Bong.) Carrière, *Pseudotsuga menziesii* (Mirb.) Franco, *Fagus sylvatica* L.) located in the Afan forest, South Wales, United Kingdom. While these species are not the same as those collected in our Coweeta field site, they contain the xylem morphological types that are found in Coweeta forests. We did not expect there to be a significant difference between the relative response of different species to root moisture content based on two lines of evidence: (1) evidence from Coweeta forests suggests that topographic position (a proxy for soil moisture content) is a stronger control than species on root strengths (Hales et al., 2009); and (2) evidence from testing of stem wood moisture contents from a wide range of species demonstrated a similar weakening of roots for all species (Kretschmann, 1999, Winandy and Rowell, 2005). We collected roots from shallow pits (<10 cm depth) excavated in hollows, with a front face 80 cm downslope of 10 randomly chosen trees. Trees were located in single species plantations, so there were unlikely to be other species included in these samples.

Root Distribution Measurements

We measured the total belowground root biomass and distribution for every pit in the field experiment. At fixed interval depth increments (0–10, 10–25, 25–45, 45–60, >60 cm) we collected all subsurface biomass by sieving material through a 2 mm mesh sieve in the field. All biomass was washed and dried in a 60°C force-draft oven until a constant weight was achieved and final biomass was determined. Unfortunately 2 sample bags were mislabelled in *L. tulipifera* hollows pits, which we remove from our analyses on root distributions. We also determined the vertical distribution (from surface to saprolite) of roots from all pits using image analysis (Hales et al., 2009). The size and depth distribution of roots within each pit was determined by painting roots within a 40 cm wide vertical swath that intersected the front face of the pit wall (closest to the tree of interest). We mapped the roots that intersected the vertical pit wall by cutting each root as close to the face as possible. This method is similar to the vertical trench wall method that is commonly used to measure root distributions (Noordwijk et al., 2000). We then photographed the pit wall and imported the photographs into a digitising program (Golden Software's Didger). Each photograph was rectified using tie points designated by measuring tapes in both the vertical and horizontal directions in the pit. We estimated the diameter of each root by drawing a line across the root and measuring its length. The exported data contained information about both the location and diameter of the root. Spatial resolution of the positions of the roots was 1 cm. Diameters were measured with an error of 0.05 mm, reflecting errors due to the optical properties of the camera (Hales et al., 2009). Roots that were oriented at an oblique angle to the main face had an elliptical cross section that was measured along its minor axis.

Root Tensile Strength Measurements

In the field experiment, for each replicate pit and soil depth, we excavated and pulled a minimum of 30 roots until failure using a 20 kg Pesola spring scale (Hales et al., 2009, Schmidt et al., 2001). For each pulled root, root diameter was measured in the field with digital calipers to the nearest 0.1 mm (Hales et al., 2013). Before pulling, roots were identified as belonging to the species of interest based on identifying features such as odor, bark color, and branching pattern. *B. lenta* roots had a distinctive wintergreen smell, black lenticels, and pinnately-branching, ectomycorrhizal fine roots. *L. tulipifera* first-order roots were larger diameter than most other species present, and light yellow in color.

Following the methods described in Hales et al. (2013), we developed linear regressions predicting force at root failure (N) as a function of root cross-sectional area (mm^2) (PROC REG, SAS v9.4, Cary, NC USA) for each species, topographic position, replicate pit and soil depth. The slope of each force-area regression has units of tensile strength (N/mm^2) (Fig. 2). There is no clear consensus on how best to derive the relationship between root force at failure and diameter. Various studies have suggested a linear regression between force and diameter (e.g. Hathaway and Penny, 1975); others choose a second order polynomial relationship between force and diameter (e.g. Schmidt et al., 2001); or a power law relationship (with an exponent of 1.7) (Riestenberg and Sovonick-Dunford, 1983). Other studies choose to calculate the individual root tensile strength by dividing the force at failure by cross sectional area of each individual root (e.g. Genet et al., 2005, Pollen and Simon, 2005, Zhang et al., 2014). The individual root tensile strength is then regressed against diameter to produce a power law relationship between diameter and strength. This final method is statistically autocorrelated because it regresses the tensile strength of individual roots (units of force divided by diameter squared) against root diameter, leading to the potentially erroneous conclusion that smaller diameter roots are proportionally stronger than larger diameter roots. We choose to plot a linear regression between force at failure and root cross sectional area as it is the equivalent to plotting a second-order polynomial of force at failure against diameter. Also, the slope of the linear regression has units of

megapascals, so represents the tensile strength of the sample of roots (hereafter termed the sample tensile strength) that we tested. To test whether a linear correlation explains the data we tested for correlation between the residuals of each linear regression and root cross-sectional area. Results for the residuals of all pits and depths had P values close to 1 and R^2 of less than 0.1, suggesting that roots of smaller diameter were not significantly stronger than those of larger diameter.

Soil Moisture Measurements

In the field, adjacent to each pit, and for the entire growing season prior to excavation, we continuously measured volumetric soil moisture content and soil temperature hourly at three depths (0–30, 30–60 and 60–90 cm). Soil temperature was measured with a type-T thermocouple junction encased in a sealed aluminium sheath. Soil moisture content was estimated using time domain reflectometry (CS616, Campbell Scientific Inc.) from 30 cm long probes oriented vertically in the soil. The measured period output from each probe (τ_m , μs) was corrected (τ_c , μs) for temperature-dependency using:

$$\tau_c = \tau_m + (20 - T) \cdot (0.526 - 0.052 \cdot \tau_m + 0.00136 \cdot \tau_m^2), \quad (1)$$

where T is soil temperature in ($^{\circ}\text{C}$). Soil specific calibrations were made in the lab that related τ_m to θ .

Laboratory-based Root Moisture-Sample Tensile Strength Measurements

In the laboratory experiment, we soaked roots overnight in a water bath in a vacuum chamber until saturated, defined as successive measurements with unchanging mass, to determine maximum moisture content (M_{\max}). Roots were then air dried for 48 hours or until the mass was constant during reweighing, to determine dry mass (M_{\min}). Roots were then soaked for times ranging between 15 minutes and 2 hours, their mass was measured, converted into relative moisture content ($M_{\text{rel}} = (M_{\max} - M_{\text{act}}) / (M_{\max} - M_{\min})$) and root tensile force at failure measured using a spring scale (described above). Sample tensile strengths were

calculated by regressing force at failure against root cross sectional area for roots grouped by root moisture content (0–20%, 20–40%, 40–60%, 60–80%, 80–100%), forcing the relationship through the origin.

Statistical Analyses of Field and Laboratory Data

To explore how root distributions and sample tensile strengths varied with topography and soil moisture measured at each site, we performed the following: (1) a test of whether the depth distribution of root biomass varied with convergent or divergent topography; (2) a test of the difference in sample tensile strength as a function of species and topography; (3) a test of the relationship between sample tensile strength and field soil moisture for different species; and (4) a test of the relationship between sample tensile strength and root moisture and species.

Statistical test 1 examined the hypothesis that parameter estimates for the root distribution in the field experiment versus soil depth relationships were the same among topographic positions (nose and hollow) using a repeated-measure, mixed effects, nonlinear model (PROC NLMIXED, SAS v9.4, Cary, NC USA) (Peek et al., 2002). For the cumulative root biomass versus soil depth relationship, the function had the following form:

$$M_R = \beta_0 + \beta_1 \cdot (1 - e^{-\beta_2 \cdot D}) \quad (2)$$

where M_R is the cumulative root biomass (kg), D is soil depth (cm), and β_0 , β_1 and β_2 represent the intercept, the cumulative total root biomass (i.e., the upper limit) and the rate of increase in the cumulative root biomass with each unit soil depth, respectively. After fitting the model for both topographic positions with replicate pit as the experimental unit, we tested for significant differences among the rate of increase and model parameters using custom contrast statements.

Statistical test 2 examined the hypothesis that the force required to break a root of given diameter (i.e., tensile strength) was the same among species (*B. lenta* and *L. tulipifera*) and topographic positions (nose and hollow) using a two-factor ANOVA model

(PROC GLM, SAS v9.4, Cary, NC USA). We used a post-hoc comparison on the lsmeans with a Tukey adjustment.

The third hypothesis was that root tensile strength declined as a function of increasing soil moisture after accounting for differences in strength among species (*B. lenta* and *L. tulipifera*). Directional responses were expected from previously reported relationships between root strength and moisture content (Hales et al., 2013); thus, statistical tests were performed at the $\alpha=0.05$, 1-tailed level. Slopes of the lines described above in the root tensile strength methods were then used as a response variable, after transforming them with a log function to achieve normality. The log values of root strength per unit diameter (MPa) data were then plotted against mean fractional soil moisture content of the soil depth from which roots were sampled. We tested for differences in the mean root tensile strength of each replicate pit depth as influenced by soil moisture with species as a covariate (PROC GLM, SAS v9.4, Cary, NC USA).

Our fourth statistical test assessed the relationship between root tensile strength and root moisture by species. We used the root tensile strengths determined from the fitted relationships above (regressing force at failure against root cross sectional area) as the response variable, with species as replicate, and root moisture class (0–20%, 20–40%, 40–60%, 60–80%, 80–100%) as the classification variable (PROC GLM SAS v9.4, Cary, NC USA). We used a post-hoc comparison on the lsmeans of root moisture class with a Tukey adjustment. Again, directional responses were expected from previously reported relationships between root strength and moisture content (Hales et al., 2013); thus, statistical tests were performed at the $\alpha=0.05$, 1-tailed level.

Fibre Bundle Model Calculations of Root Reinforcement

For each of our field experimental pits, we calculated the average lateral root reinforcement using a load-distributed fibre bundle model (FBM), where load is distributed evenly across unfailed roots in the bundle (Bischetti et al., 2009). In each pit, we calculated the diameter of each individual root crossing the planar pit face. Poor light lowered the resolution of pit photos for three of the pits located in nose locations and we removed the results (*L. tulipifera* nose replicate 3, *B. lenta* nose replicates 1 and 3). We converted the diameter distribution at each pit face into a distribution of force at failure by multiplying the cross sectional area of each root by its tensile strength. Root tensile strength for each species and soil moisture content was determined based on the slope of the regression between tensile strength and soil moisture. Hence for each root, we determined the species and soil moisture content and assigned a force at failure. To determine the strength of the whole bundle of roots, we added load in 50 Pa increments and distributed it equally amongst the roots in the bundle (following Bischetti et al., 2009). If a root broke, the load was redistributed amongst the remaining roots and we continued to load, break, and redistribute load until the bundle was stable at that particular load increment. We continued to add load incrementally until all roots within the bundle failed. To calculate root reinforcement we divided the force at which all roots failed by soil depth (as pits were 1 m wide), and assumed that the factor associated with roots being inclined at a range of angles relative to the shear zone was 1 (Cohen et al., 2011).

Slope stability modelling

We tested for the effects of changes in root reinforcement on the stability of our experimental hollow pits by calculating changes to the factor of safety (FS) of each hollow for each change in the depth of saturated soil during a precipitation event that filled a dry soil to saturation. FS (unitless) for each scenario followed the Mohr-Coulomb equation (Selby, 1993):

$$FS = \frac{c' + (\gamma - m\gamma_w)z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta}, \quad (3)$$

where c' is the cohesion contribution of both roots and soil (N/m^2); γ and γ_w are the unit weight of dry soil ($17,600 \text{ N/m}^3$) and water ($9,800 \text{ N/m}^3$) respectively; m is the ratio between soil depth and depth of water table (unitless); β is the field-measured slope angle; z is the soil depth at the base of the pit (m); and ϕ' is the friction angle. We input measurements of soil cohesion (0 Pa) and friction angle (35°) based on triaxial tests of hollow soils collected within the Coweeta Hydrologic Laboratory (Hales et al., 2009).

Our modelling exercise seeks to understand the maximum magnitude of the possible dynamic effect of changes in root moisture content on slope stability, rather than specifically recreate the slope stability for a given rainstorm event. We model a system where the dominant source of soil moisture is convergent throughflow in the soil column that fills the soil upward from the bedrock surface (Montgomery and Dietrich, 1994). For each modelled hollow, we used the rooting distributions measured in the field. Each root diameter was assigned a tensile strength based on the soil moisture conditions at that point in the soil column. Roots that fell above the water table are “dry” (here we use a value that is equivalent to a soil moisture content of 0.10), while those below the water table are “wet” (here we use the maximum soil moisture content). We then calculated the additional lateral cohesion across the soil column for each soil moisture condition using our FBM and used this to calculate FS. We calculated FS for different saturated soil depths by varying both c' and m , and compared this to results with a constant c' (equal to the dry condition) and a variable m . As we are looking to specifically isolate the effects of changes in root tensile strength on stability, we have used a very simple model of hydrology that does not account

for pore water pressures caused by infiltration (Iverson, 2000), changes in soil moisture content associated with transpiration and other ecohydrologic processes (Hwang et al., 2009, Lepore et al., 2013), and additional soil strengths caused by suction forces in unsaturated soils (Veylon et al., 2015). Wet soils also change the frictional strength between root and soil, often leading to the pull out of small roots (Pollen, 2007). Root pull out reduces the total reinforcement, compounding any reduction in cohesion associated with loss of root strength. Also, our simplified model does not account for the fact that the unsaturated soil column will have a variable soil moisture content, and therefore roots at different saturation states. However, we are simply attempting to understand the magnitude of any potential soil moisture effects on cohesion, rather than explicitly model specific storms.

Results

Topographic controls on soil moisture and total biomass

As expected, soils in zones of greater topographic convergence and lower average slope were wetter on average. Average daily soil moisture content was higher in the *L. tulipifera* sites than the *B. lenta* sites, and noses were drier than hollows (species effect $F_{1,8.3} = 139.88$, $P < 0.001$; topo effect $F_{1,8.3} = 7.02$, $P = 0.03$; no interaction). Across all topographic positions and depths, *B. lenta* sites had average soil moistures of 0.27 while *L. tulipifera* sites had an average of 0.58. Across all species and depths, hollows were 18% wetter than noses. Soil moisture varied by depth, but this depended on the species (depth by species interaction $F_{2,15} = 5.91$, $P = 0.01$). Within a particular species, the soil moisture was consistent with depth and topographic position (no species by topographic by depth interaction). Soil moisture didn't vary significantly among depths in the *B. lenta* pits; but within the *L. tulipifera* pits, the shallowest depth was significantly wetter than the deeper soil layers, which didn't differ.

Total belowground biomass did not differ between hollows (1303 g \pm 347 g SD) and noses (1299 g \pm 569 g; $F_{1,8} = 2.00$, $P = 0.22$). All pits showed a characteristic exponential rise to a maximum in cumulative root biomass with increasing soil depth (Fig. 3A & B). Root

distributions varied more among pits than between topographic positions (for β_0 , $F_{1,7} = 0.82$, $P = 0.39$; for β_1 , $F_{1,7} = 1.15$, $P = 0.32$; and for β_2 , $F_{1,7} = 0.01$, $P = 0.95$.) (Fig 3C & D). The modelled upper cumulative biomass limit for hollows was 0.92 kg, and 0.69 kg for noses.

Relationships between topography and root strength

Sample tensile strength varied among species (species effect $F_{1,11} = 16.16$, $P = 0.004$), with *B. lenta* roots 1.3 times stronger than *L. tulipifera* roots (lsm means 19.4 MPa vs. 8.3 MPa, respectively). Once accounting for the species effect, no systematic differences in sample tensile strength were found between topographic positions (topographic effect $F_{1,11} = 0.79$, $P = 0.39$, interaction $F_{1,11} = 1.23$, $P = 0.29$) (Fig. 4).

The maximum topographic slope measured in the field did not correlate with sample tensile strength. There was also no significant relationship (with 95% confidence) between drainage area and sample tensile strength (linear model $F_{1,24} = 2.38$, $P = 0.13$).

Root strength and soil moisture

In the field, sample tensile strength declined with increasing soil moisture content. The variation in log-transformed sample tensile strength (MPa) varied systematically between species and declined linearly with increasing soil moisture content (model $R^2 = 0.70$, $F_{4,29} = 149.9$, $P < 0.001$). For *B. lenta* log-transformed sample tensile strength (MPa) = $1.55 - 2.318 * \text{fractional soil moisture}$; and for *L. tulipifera* log-transformed root tensile strength (MPa) = $0.602 - 0.138 * \text{fractional soil moisture}$ (Fig. 5A).

In our laboratory experiment root moisture content significantly affected sample tensile strength ($F_{6,14} = 11.78$, $P < 0.01$) (Fig. 5B). For all species examined, there was little difference in tensile strength at root moisture contents between 0% and 60%, although the root strength decreased at higher root moisture contents. Across all species, there was a 40% decline in root strength from 20–40% root moisture content to 80–100% root moisture (lsm means 20.7 vs. 12.2, $P = 0.0014$).

The relationships between tensile strength and root moisture were then used to model slope stability and highlight the potential dynamic role of roots in controlling slope stability. As the soil saturates, the decline in factor of safety was greater in the *B. lenta* hollows compared to the *L. tulipifera* hollows due to the steep slope on the moisture vs. tensile strength regressions (Fig. 6A). All *L. tulipifera* hollows show very little difference between a constant root reinforcement and a dynamic one because of the shallow slope on the soil moisture-tensile strength curve. In the *B. lenta* hollow, slope stability decreases non-linearly with soil saturation. When the level of saturation is close to the bedrock-soil interface, it intersects with a relatively small number of roots, so the relative loss of soil strength is small. However, as the soil saturation level proceeds upward through the soil column, it intersects a greater number of roots causing a proportionally larger decrease in soil strength. When the soil saturates, the high concentration of roots in the top 20 cm of the soil column causes the rapid non-linear decline in factor of safety. This simple analysis suggests that magnitude of dynamic root reinforcement reduction could cause a significant and rapid weakening of soil strength as soils approach saturation (Fig. 6A). This experimental relationship is simplified by the bimodal root moisture conditions that we used to constrain the model. It is likely that during a shallow landslide initiation event, where landslide initiation is governed by hydrologic processes acting at different temporal scales (Iverson, 2000), that direct precipitation would weaken roots at the soil surface as well as the basal roots weakening as throughflow and groundwater saturate the base of the soil column. Regardless of the configuration of soil moisture conditions that are applied to the system, our simple model demonstrates that for some species of trees, soil moisture can significantly reduce the apparent cohesion provided by roots and decrease slope stability.

Discussion

Our experimental setup allowed us to compare mature trees that have grown under different soil moisture conditions. We observed that topographic position did not significantly affect root distribution; however, dynamic, short-term soil moisture variability may be a significant control on root reinforcement of slopes.

Root distributions and tensile strength at the hillslope scale

The belowground architecture of the root mass, measured in our study through direct measurements of biomass and the diameter distribution of roots along pit faces did not show a consistent difference between wetter and drier topographic positions. Instead, our data show that there is significant variability in both cumulative root biomass and distribution with depth at both topographic positions, suggesting that our small sample size was not adequate to capture any potential systematic changes in root biomass or distribution between topographic positions. Systematic differences in root distributions were shown in other pits in the Coweeta Hydrologic Laboratory, where there hollows had more evenly distributed roots with depth than noses (Hales et al., 2009). This contrasts the ecohydrologic modelling results from water-limited environments that suggest a strong relationship between root extent and soil moisture conditions (Laio et al., 2006, Preti et al., 2010, Sivandran and Bras, 2012, Tron et al., 2014). Empirical evidence of changes to rooting structure with soil moisture contents suggest a number of possible responses where this is the limiting resource. Nicotra et al. (2002) compared the belowground biomass distribution of different species that evolved under high and low rainfall regimes. They showed that plants that evolved under low rainfall systems tended to allocate a greater proportion of mass to main root axis and have a smaller main root axis diameter than those that evolved under high rainfall regimes. Evidence for acclimation also exists; seedlings exposed to an experimentally controlled 33% reduction in rainfall over 5 years responded by increasing their root to shoot ratio, but maintained a similar total biomass to the non-manipulated sites (Joslin et al., 2000). Comparison of *Pinus pinaster* Aiton plantations with different water table

depths and soil fertilities showed that while the total biomass did not change significantly with different soil moistures, drier sites were more shallowly rooted and had fewer coarse roots with depth (Bakker et al., 2006). After six years of irrigation that increased soil moisture by 41%, total belowground carbon allocation in longleaf pine savannas roughly doubled, and was preferentially distributed in shallow soil layers (Ford et al., 2012). These studies suggest that rooting distributions should change in areas with greater precipitation (Ford et al., 2012, Joslin et al., 2000, Nicotra et al., 2002) or higher average soil moisture contents (Bakker et al., 2006, Ford et al., 2012, Hales et al., 2009), yet our results are not consistent with this interpretation. One possible reason is that while there is a significant 18% difference in soil moisture content between our nose and hollow sites, the drier nose sites are still relatively wet; and with evenly distributed precipitation at this site, that statistically occurs every three days (Swift et al., 1988) these differences may not be enough to influence root architecture.

Differences between the average strength of roots between our *B. lenta* and *L. tulipifera* sites could be related to either differences in root structure as reflected by wood densities or by differences in soil moisture content between the populations of roots. The majority of root strength depends on the strength of the vascular tissue (Genet et al., 2005, Hathaway and Penny, 1975), which has the same overall tissue structure as stem wood. Wood density has been shown to correlate to wood strength in numerous hardwood species (Beery et al., 1983, Hacke et al., 2001), as it reflects the relative proportion of voids and non-cell wall material versus cell wall material (e.g., cellulose and lignin). While wood density does not control plant function, it correlates with a number of hydraulic and strength properties of plants, e.g. density increases in more drought tolerant species (Lachenbruch and McCulloh, 2014). Denser, stronger woods have higher concentrations of cellulose and lignin (Hacke et al., 2001), consistent with observations of stronger roots (Genet et al., 2005, Hales et al., 2009, Kerstens and Verbelen, 2002, Yang et al., 2016, Zhang et al., 2014). *B. lenta* (600 kg/m³) wood is up to twice as dense as *L. tulipifera* (300–400 kg/m³) wood (Chave et al., 2009), so some of the difference in the average strength of the roots of these species could be accounted for by density.

Local soil moisture controls on root tensile strength

Within a particular species, roots that were excavated from soils with lower soil moisture contents were significantly stronger than those excavated at higher soil moisture conditions (Fig. 5). The possibility that roots may weaken with differences in water content is consistent with both observations of weakening of stem wood with differences in moisture content and with our experimental data, where root tensile strengths decreased with changes in moisture content. The observation that stem wood is weaker in tension at different moisture contents has been shown for a large number of tree species (Kretschmann, 1999). This decrease in strength has been related to the accumulation of water in the cell wall, called bound water, which decreases the strength of bonds between organic polymers of the cell wall. Water accumulates in the cell wall between a “dry” condition and a fibre-saturation point, after which water accumulates in the cell cavity and does not affect wood strength. Therefore in stem wood, there is a non-linear relationship between wood strength and moisture content, with dry wood being up to twice as strong as wet wood (Winandy and Rowell, 2005).

It is reasonable to assume that the mechanism controlling stem wood strength would likely affect the strength of root xylem, as these are the same tissue types. Our controlled experimental observations support this contention. The experiments show that for each of the three different tree species tested, roots with lower moisture contents (<60%) were stronger than when they were wetter. There were differences both in the total tensile strength between different species and the magnitude of the moisture effect on root strength. *F. sylvatica* roots lost 20% of their dry strength when saturated, while *P. sitchensis* roots lost ~50% of their dry strength when saturated. A similar species effect was seen in experiments on stem wood. In tensile tests of stem wood, *B. lenta* green stem wood (tensile strength of 3,000 kPa) was less than half the strength of wood with 12% moisture content (6,600 kPa), while *L. tulipifera* was less susceptible to these effects with green wood (3,500 kPa) being only slightly weaker than wood at 12% moisture content (3,700 kPa) (Kretschmann, 1999). Tensile strengths at different root moisture contents have been calculated in one other study

(Yang et al., 2016). The results here suggested that root strengths were highest at root moisture contents between 18% and 31% greater than that for dry roots. Roots with moisture contents less than 18% were considerably weaker (although only for 3 of the 4 species tested), attributed to a reduction in root elasticity (Yang et al., 2016). Roots that were wetter than 31% were also weaker, consistent with our study. In our study at root moisture contents of 0–20%, *P. sitchensis* roots were weaker, but the roots of the other two species were not discernably weaker than for other soil moisture contents (Fig. 5B). While there is no clear physical reason for why roots from a particular species are more brittle in dry condition, in both this study and Yang et al.'s (2016) study there does appear to be differences in response at the species level.

We show that our field measured root tensile strengths decrease with increasing volumetric soil moisture, consistent with controlled laboratory experiments on both stem wood (Kretschmann, 1999, Winandy and Rowell, 2005) and roots (this study). Our laboratory observations demonstrate that roots absorb water rapidly, and can move from completely dry to saturated within a few hours, suggesting that root strengths are likely to change over the course of a large storm event. *B. lenta* root tensile strengths varied strongly with soil moisture, while *L. tulipifera* roots showed a weaker relationship, again consistent with literature reports. Our results suggest that during storms, increases in soil moisture content are likely to reduce the magnitude of root reinforcement. The implication is that during the course of a storm, root cohesion decreases as pore pressure increases, dynamically reducing slope stability.

Dynamic controls of root reinforcement on slope stability

The observation that root tensile strength varies with root and soil moisture content suggests that the magnitude of root reinforcement may decrease over the course of a landslide-producing storm. Our calculations of change in factor of safety with different soil moisture contents illustrate the potential magnitude of this positive feedback. Most of the

strength reduction occurs when the soil is close to saturation. This is because the greatest proportion of roots is found in the upper 20 cm of soil.

The relationship between root strength and soil moisture implies that tree roots adjust strength rapidly due to changes in soil moisture content. The timescale at which root water content changes is important for governing the rate of any dynamic response. While we are unaware of studies that directly measure root moisture content and soil moisture content, studies showing rapid increases in stem water content with increasing soil water content during storm events allow us to infer that roots saturate quickly (Matheny et al., 2015). Other lines of evidence also allow us to infer that root moisture saturation likely occurs rapidly (minutes-hours). In transpiration modeling, when stomata are open plants uptake water at a rate that is proportional to a difference in water potential between the soil and in the plant. When stomata close (as during a rain event, or at night for most plants), the plant water potential rapidly equilibrates to the average soil water potential that the total root biomass is exposed to (Améglio et al., 1999, ; but see Donovan et al., 2003, Hinckley et al., 1978, Kramer and Boyer, 1995). While, the soil and root moisture contents (%) will be different, due to differing air-filled porosity, they will both be at a water potential of 0 MPa following a storm that saturates the soil. Our laboratory experiments may provide further insight into this process. In our experiments, changes in root moisture of 20% occurred within 15–30 minutes, suggesting that the lag between increases and decreases in soil moisture and changes in root moisture content may be shorter than the duration of the largest Appalachian storms. Significant landsliding in the southern Appalachians occurs during storms that take place over many hours to days, considerably longer than the time it takes to saturate roots (Wooten et al., 2016). In the laboratory, completely dry roots usually took 2 hours to saturate. Root moisture content will also be affected by transpiration, which would likely decrease root moisture content relative to the surrounding soil. However, during large storms, it could be expected that transpiration rates are low to negligible and root moisture would more closely follow soil moisture contents.

The implications of these results are that when creating slope stability models at the regional scale that we may significantly overestimate root reinforcement, and therefore slope stability. This process appears to be species dependent, so we would expect hollows in mixed species forests, such as those in our field study site, to have a range of responses. In this case, it may be difficult to estimate which hollows may have a dynamic response without detailed understanding of the species composition of each hollow. This process may be significant for monocultural forests such as plantation or managed forests. For example, our laboratory results suggest that *P. sitchensis* and *P. menziesii* can lose up to 50% of their strength when wet (compared to dry). Both of these species are cultivated in monoculture for wood production (e.g. The Forestry Industry Council of Great Britain, 1998) or where one or the other is the dominant species in naturally occurring forests in the Pacific Northwest of the USA (Halpern and Spies, 1995). In these forests, the slopes may become less stable with time as the soil saturates. More work is required to understand how many common tree species have significant soil-moisture controls on tensile strength and to relate this to regional or hillslope-scale slope stability models.

Conclusions

We designed field and laboratory experiments to test how topography and soil moisture content affect the root reinforcement on slopes. In the field, root biomass and its distribution with depth did not vary between relatively dry noses and wetter hollows, likely because the magnitude of the difference in soil moisture is small between these locations. Sample tensile strength varies significantly with soil moisture content, where wetter roots are weaker than drier roots. A similar reduction in strength is shown in the laboratory when we control for root moisture content. Fibre-bundle modelling of root reinforcements shows that root reinforcement is much lower as roots get wetter. When accounting for the effects of soil-moisture controlled root reinforcement, the factor of safety can be up to half of the value calculated using a constant root reinforcement.

Acknowledgements

This study was supported by the US Department of Agriculture Forest Service, Southern Research Station, and by National Science Foundation grants DEB-0823293 and DEB-1440485 to the Coweeta LTER programme at the University of Georgia. Any opinions, findings, conclusions or recommendations expressed in the material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the University of Georgia. Post-hoc analysis was supported by NERC grant NE/J009067/1 to Hales. Many thanks to Joseph Davis, Taehee Hwang, Robert McCollum, and Neal Muldoon who helped with field data collection. Laurence Lovell assisted with the laboratory experimentation. Eli Lazarus, Robert Parker, Josh Roering, and two anonymous reviewers provided insightful reviews of an early version of the manuscript.

References

- Abernethy B, Rutherford ID. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes* **15**: 63-79. DOI: 10.1002/hyp.152
- Améglio T, Archer P, Cohen M, Valancogne C, Daudet F-a, Dayau S, Cruiziat P. 1999. Significance and limits in the use of predawn leaf water potential for tree irrigation. *Plant and Soil* **207**: 155-167. DOI: 10.1023/a:1026415302759
- Anderson CJ, Coutts MP, Ritchie RM, Campbell DJ. 1989. Root extraction force measurements for Sitka Spruce. *Forestry* **62**: 127-137
- Bakker MR, Augusto L, Achat DL. 2006. Fine root distribution of trees and understory in mature stands of maritime pine (*Pinus pinaster*) on dry and humid sites. *Plant and Soil* **286**: 37-51
- Beery WH, Geza I, McLain TE. 1983. Quantitative wood anatomy-relating anatomy to transverse tensile strength. *Wood and Fiber Science* **15**: 395-407
- Benda L, Dunne T. 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research* **33**: 2849-2863
- Bischetti GB, Chiaradia E, Epis T, Morlotti E. 2009. Root cohesion of forest species in the Italian Alps. *Plant and Soil* **324**: 71-89. DOI: 10.1007/s11104-009-9941-0
- Bischetti GB, Chiaradia EA, Simonato T, Speziali B, Vitali B, Vullo P, Zocco A. 2005. Root strength and root area ratio of forest species in Lombardy (Northern Italy). *Plant and Soil* **278**: 11-22
- Bolstad PV, Swank WT, Vose JM. 1998. Predicting Southern Appalachian overstory vegetation with digital terrain data. *Landscape Ecology* **13**: 271-283
- Bourrier F, Kneib F, Chareyre B, Fourcaud T. 2013. Discrete modeling of granular soils reinforcement by plant roots. *Ecological Engineering* **61**: 646-657
- Britain TFICoG. 1998. A reference for the forestry industry. The Forestry Industry Council of Great Britain: Stirling, UK

- Cairns MA, Brown S, Helmer EH, Baumgardner GA. 1997. Root biomass allocation in the world's upland forests. *Oecologia* **111**: 1-11
- Casadei M, Dietrich WE. 2003. Controls on shallow landslide size. In *Proceedings of the 3rd International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*: Davos, Switzerland; 91-101.
- Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE. 2009. Towards a worldwide wood economics spectrum. *Ecology Letters* **12**: 351-366. DOI: 10.1111/j.1461-0248.2009.01285.x
- Cohen D, Schwarz M, Or D. 2011. An analytical fiber bundle model for pullout mechanics of root bundles. *Journal of Geophysical Research* **116**: doi:10.1029/2010JF001886
- Coutts MP. 1983. Root architecture and tree stability. *Plant and Soil* **71**: 171-188
- Crozier MJ, Vaughan EE, Tippett JM. 1990. Relative instability of colluvium-filled bedrock depressions. *Earth Surface Processes and Landforms* **15**: 329-339. DOI: 10.1002/esp.3290150404
- Day FP, Phillips DL, Monk CD. 1988. Forest Communities and Patterns. In *Forest Hydrology and Ecology at Coweeta*, Swank WT, Crossley DA (eds). Springer-Verlag: New York.
- Donovan LA, Richards JH, Linton. MJ. 2003. Magnitude and mechanisms of disequilibrium between predawn plant and soil water potentials. *Ecology* **84**: 463-470
- Douglass JE, Swank WT. 1976. Multiple use in southern Appalachian hardwoods—a 10-year case history. XVI IUFRO World Congress Division 1 Proc.: 425–436
- Fan C-C, Su C-F. 2009. Effect of soil moisture content on the deformation behaviour of root-reinforced soils subjected to shear. *Plant and Soil* **324**: 57-69. DOI: 10.1007/s11104-008-9856-1
- Ford CR, McGee J, Scandellari F, Hobbie EA, Mitchell RJ. 2012. Long- and short-term precipitation effects on soil CO₂ efflux and total belowground carbon allocation. *Agricultural and Forest Meteorology* **156**: 54-64. DOI: <http://dx.doi.org/10.1016/j.agrformet.2011.12.008>
- Gabet EJ, Dunne T. 2002. Landslides on coastal sage-scrub and grassland hillslopes in a severe El Niño winter: The effects of vegetation conversion on sediment delivery. *Geological*

Society of America Bulletin **114**: 983-990. DOI: 10.1130/0016-7606(2002)114<0983:locssa>2.0.co;2

Gabet EJ, Dunne T. 2003. A stochastic sediment delivery model for a steep Mediterranean landscape. Water Resources Research **39**: doi:10.1029/2003WR002341

Genet M, Li M, Luo T, Fourcaud T, Clément-Vidal A, Stokes A. 2011. Linking carbon supply to root cell-wall chemistry and mechanics at high altitudes in *Abies georgei*. Annals of Botany **107**: 311-320

Genet M, Stokes A, Salin F, Mickovski SB, Fourcaud T, Dumail J-F, van Beek R. 2005. The influence of cellulose content on tensile strength of tree roots. Plant and Soil **278**: 1-9

Ghestem M, Veylon G, Bernard A, Vanel Q, Stokes A. 2013. Influence of plant root system morphology and architectural traits on soil shear resistance. Plant and Soil **377**: 43-61. DOI: 10.1007/s11104-012-1572-1

Hacke UG, Sperry JS, Pockman WT, Davis SD, McCulloch KA. 2001. Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure. Oecologia **126**: 457-461

Hales TC, Cole-Hawthorne C, Lovell L, Evans S. 2013. Assessing the accuracy of simple field based root strength measurements. Plant and Soil **372**: 553-565. DOI: 10.1007/s11104-013-1765-2

Hales TC, Ford CR, Hwang T, Vose JM, Band LE. 2009. Topographic and ecologic controls on root reinforcement. Journal of Geophysical Research **114**: doi:10.1029/2008JF001168

Halpern CB, Spies TA. 1995. Plant Species Diversity in Natural and Managed Forests of the Pacific Northwest. Ecological Applications **5**: 913-934. DOI: 10.2307/2269343

Hathaway RL, Penny D. 1975. Root Strength in Some *Populus* and *Salix* Clones. New Zealand Journal of Botany **13**: 333-344

Hinckley TM, Lassoie JP, Running SW. 1978. Temporal and spatial variations in the water status of forest trees. Forest Science Monograph **20**: 1-72

Hursh CR. 1941. The geomorphic aspects of mudflows as a type of accelerated erosion in the Southern Appalachians. American Geophysical Union Transactions **2**: 253-254

- Hwang T, Band L, Hales TC. 2009. Ecosystem processes at the watershed scale: Extending optimality theory from plot to catchment. *Water Resources Research* **45**. DOI: 10.1029/2009wr007775
- Hwang T, Band LE, Hales TC, Miniati CF, Vose JM, Bolstad PV, Miles B, Price K. 2015. Simulating vegetation controls on hurricane-induced shallow landslides with a distributed ecohydrological model. *Journal of Geophysical Research: Biogeosciences*: 2014JG002824. DOI: 10.1002/2014JG002824
- Iida T. 1999. A stochastic hydro-geomorphological model for shallow landsliding due to rainstorm. *Catena* **34**: 293-313. DOI: [http://dx.doi.org/10.1016/S0341-8162\(98\)00093-9](http://dx.doi.org/10.1016/S0341-8162(98)00093-9)
- Iida T, Okunishi K. 1983. Development of hillslopes due to landslides. *Zeitschrift für Geomorphologie* **46**: 67-77
- Iverson RM. 2000. Landslide triggering by rain infiltration. *Water Resources Research* **36**: 1897-1910
- Ji J, Kokutse N, Genet M, Fourcaud T, Zhang Z. 2012. Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (*Robinia pseudoacacia*) and Arborvitae (*Platycladus orientalis*) stands on the Loess Plateau, China. *Catena* **92**: 139-154
- Joslin JD, Wolfe MH, Hanson PJ. 2000. Effects of altered water regimes on forest root systems. *New Phytologist* **147**: 117-129
- Kerstens S, Verbelen J-P. 2002. Cellulose orientation in the outer epidermal wall of angiosperm roots: Implications for biosystematics. *Annals of Botany* **90**: 669-676
- Kramer PJ, Boyer JS. 1995. *Water relations of plants and soils*. Academic Press: San Diego
- Kretschmann DE. 1999. Mechanical properties of wood. In *Wood Handbook: Wood as an engineering material*, Service UF (ed): Madison, Wisconsin.
- Lachenbruch B, McCulloh KA. 2014. Traits, properties, and performance: how woody plants combine hydraulic and mechanical functions in a cell, tissue, or whole plant. *New Phytologist* **204**: 747-764. DOI: 10.1111/nph.13035

- Laio F, D'Odorico P, Ridolfi L. 2006. An analytical model to relate the vertical root distribution to climate and soil properties. *Geophysical Research Letters* **33**: L18401. DOI: 10.1029/2006GL027331
- Lepore C, Arnone E, Noto LV, Sivandran G, Bras RL. 2013. Physically based modeling of rainfall-triggered landslides: a case study in the Luquillo forest, Puerto Rico. *Hydrol. Earth Syst. Sci.* **17**: 3371-3387. DOI: 10.5194/hess-17-3371-2013
- Matheny AM, Bohrer G, Garrity SR, Morin TH, Howard CJ, Vogel CS. 2015. Observations of stem water storage in trees of opposing hydraulic strategies. *Ecosphere* **6**: 1-13. DOI: 10.1890/ES15-00170.1
- Milledge DG, Bellugi D, McKean JA, Densmore AL, Dietrich WE. 2014. A multidimensional stability model for predicting shallow landslide size and shape across landscapes. *Journal of Geophysical Research: Earth Surface* **119**: 2014JF003135. DOI: 10.1002/2014JF003135
- Montgomery DR, Dietrich WE. 1994. A physically based model for the topographic control on shallow landsliding. *Water Resources Research* **30**: 1153-1171
- Nicotra AB, Babicka N, Westoby M. 2002. Seedling root anatomy and morphology: an examination of ecological differentiation with rainfall using phylogenetically independent contrasts. *Oecologia* **130**: 136-145
- Noordwijk M, Brouwer G, Meijboom F, Rosário G, Oliveira M, Bengough AG. 2000. Trench Profile Techniques and Core Break Methods. In *Root Methods: A Handbook*, Smit AL, Bengough AG, Engels C, Noordwijk M, Pellerin S, Geijn SC (eds). Springer Berlin Heidelberg: Berlin, Heidelberg; 211-233.
- O'Loughlin C, Watson AJ. 1979. Root wood strength deterioration in *Pinus radiata* after clearfelling. *New Zealand Journal of Forestry Science* **9**: 284-293
- O'Loughlin C, Ziemer RR. 1982. The importance of root strength and deterioration rates upon edaphic stability in steep-land forests. In *Carbon Uptake and Allocation in Subalpine Ecosystems as a Key to Management: Proceedings of an IUFRO Workshop*; 70-77.
- Peek MS, Russek-Cohen E, Wait DA, Forseth IN. 2002. Physiological response curve analysis using nonlinear mixed models. *Oecologia* **132**: 175-180

- Pollen N. 2007. Temporal and spatial variability in root reinforcement of streambanks: Accounting for soil shear strength and moisture. *Catena* **69**: 197-205
- Pollen N, Simon A. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research* **41**: doi:10.1029/2004WR003801
- Pollen-Bankhead N, Simon A. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? *Geomorphology* **116**: 353-362
- Preti F, Dani A, Laio F. 2010. Root profile assessment by means of hydrological, pedological and above-ground vegetation information for bio-engineering purposes. *Ecological Engineering* **36**: 305-316. DOI: <http://dx.doi.org/10.1016/j.ecoleng.2009.07.010>
- Riestenberg MM, Sovonick-Dunford S. 1983. The role of woody vegetation in stabilizing slopes in the Cincinnati area, Ohio. *Geological Society of America Bulletin* **15**: 3-45
- Roering JJ, Schmidt KM, Stock JD, Dietrich WE, Montgomery DR. 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. *Canadian Geotechnical Journal* **40**: 237-253
- Sakals ME, Sidle RC. 2004. A spatial and temporal model of root cohesion in forest soils. *Canadian Journal of Forest Research* **34**: 950-958
- Schenk HJ, Jackson RB. 2002. The global biogeography of roots. *Ecological Monographs* **72**: 311-328
- Schenk HJ, Jackson RB. 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma* **126**: 129-140
- Schmidt K, Roering JJ, Stock JD, Dietrich WE, Montgomery DR, Schaub T. 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal* **38**: 995-1024
- Schwarz M, Cohen D, Or D. 2010. Root-soil mechanical interactions during pullout and failure of root bundles. *Journal of Geophysical Research* **115**: doi:10.1029/2009JF001603
- Selby MJ. 1993. Hillslope materials and processes. Oxford University Press: Oxford

- Sivandran G, Bras RL. 2012. Identifying the optimal spatially and temporally invariant root distribution for a semiarid environment. *Water Resources Research* **48**: W12525. DOI: 10.1029/2012WR012055
- Sivandran G, Bras RL. 2013. Dynamic root distributions in ecohydrological modeling: A case study at Walnut Gulch Experimental Watershed. *Water Resources Research* **49**: 3292-3305. DOI: 10.1002/wrcr.20245
- Stone EL, Kalisz PJ. 1991. On the maximum extent of tree roots. *Forest Ecology and Management* **46**: 59-102
- Swank WT, Crossley DA. 1988. *Ecological Studies, Vol. 66: Forest Hydrology and Ecology at Coweeta*. Springer-Verlag: New York
- Swift LW, Cunningham GB, Douglass JE. 1988. Climatology and hydrology. In *Forest Hydrology and Ecology*, Swank WT, Crossley DA (eds). Springer: New York; 35-55.
- Tron S, Dani A, Laio F, Preti F, Ridolfi L. 2014. Mean root depth estimation at landslide slopes. *Ecological Engineering* **69**: 118-125. DOI: <http://dx.doi.org/10.1016/j.ecoleng.2014.03.019>
- Veylon G, Ghestem M, Stokes A, Bernard A. 2015. Quantification of mechanical and hydric components of soil reinforcement by plant roots. *Canadian Geotechnical Journal* **52**: 1839-1849. DOI: 10.1139/cgj-2014-0090
- Waldron LJ. 1977. The shear resistance of root-permeated homogeneous and stratified soil. *Journal of the Soil Science Society of America* **41**: 843-849
- Waldron LJ, Dakessian S. 1981. Soil reinforcement by roots: calculation of increased soil shear resistance from root properties. *Soil Science* **132**: 427-435
- Walter H. 1973. *Vegetation of the earth in relation to climate and the ecophysiological conditions*. Springer-Verlag: New York
- Weltzin JF, McPherson GR. 1997. Spatial and temporal soil moisture resource partitioning by trees and grasses in a temperate savanna, Arizona, USA. *Oecologia* **112**: 156-164
- Winandy JE, Rowell RM. 2005. Chemistry of wood strength. In *Handbook of Wood Chemistry and Wood Composites*, Rowell RM (ed). CRC Press: Boca Raton; 303-347.

Wooten RM, Witt AC, Miniati CF, Hales TC, Aldred JL. 2016. Frequency and Magnitude of Selected Historical Landslide Events in the Southern Appalachian Highlands of North Carolina and Virginia: Relationships to Rainfall, Geological and Ecohydrological Controls, and Effects. In *Natural Disturbances and Historic Range of Variation: Type, Frequency, Severity, and Post-disturbance Structure in Central Hardwood Forests USA*, Greenberg HC, Collins SB (eds). Springer International Publishing: Cham; 203-262.

Wu TH, McKinnell III WP, Swanston DN. 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. *Canadian Geotechnical Journal* **16**: 19-34

Yang Y, Chen L, Li N, Zhang Q. 2016. Effect of Root Moisture Content and Diameter on Root Tensile Properties. *PLoS ONE* **11**: e0151791. DOI: 10.1371/journal.pone.0151791

Zhang C, Chen L, Jiang J. 2014. Why fine tree roots are stronger than thicker roots: The role of cellulose and lignin in relation to slope stability. *Geomorphology* **206**: 196-202

Table 1. Table of the topographic and biomass characteristics by species and topography (each site is the average of 3 replicate samples). Numbers in parantheses represent the one standard deviation uncertainty of each measurement. Elevation, curvature, slope, aspect, and drainage area are calculated from the ~7m North Carolina State LiDAR dataset. Curvature is the average curvature of a radius of 14m from the pit site. Drainage area is calculated using the D8 flow algorithm. Mean biomass measured for our pit locations.

Species	Topography	Elevation (m)	Curvature	Slope (°)	Aspect (°)	Drainage Area (m²)	Total belowground biomass (kg)
BELE	Hollow	1222 (25)	-2.6 (0.6)	26 (9)	5 (45)	94 (48)	1.2 (0.2)
	Nose	1252 (34)	2.8 (1.7)	23 (5)	348 (42)	8 (4)	1.6 (0.8)
LITU	Hollow	1040 (11)	-1.9 (0.7)	10 (7)	47 (31)	320 (271)	1.7
	Nose	1035 (12)	1.8 (0.8)	12 (3)	43 (56)	16 (4)	2.7 (2.1)

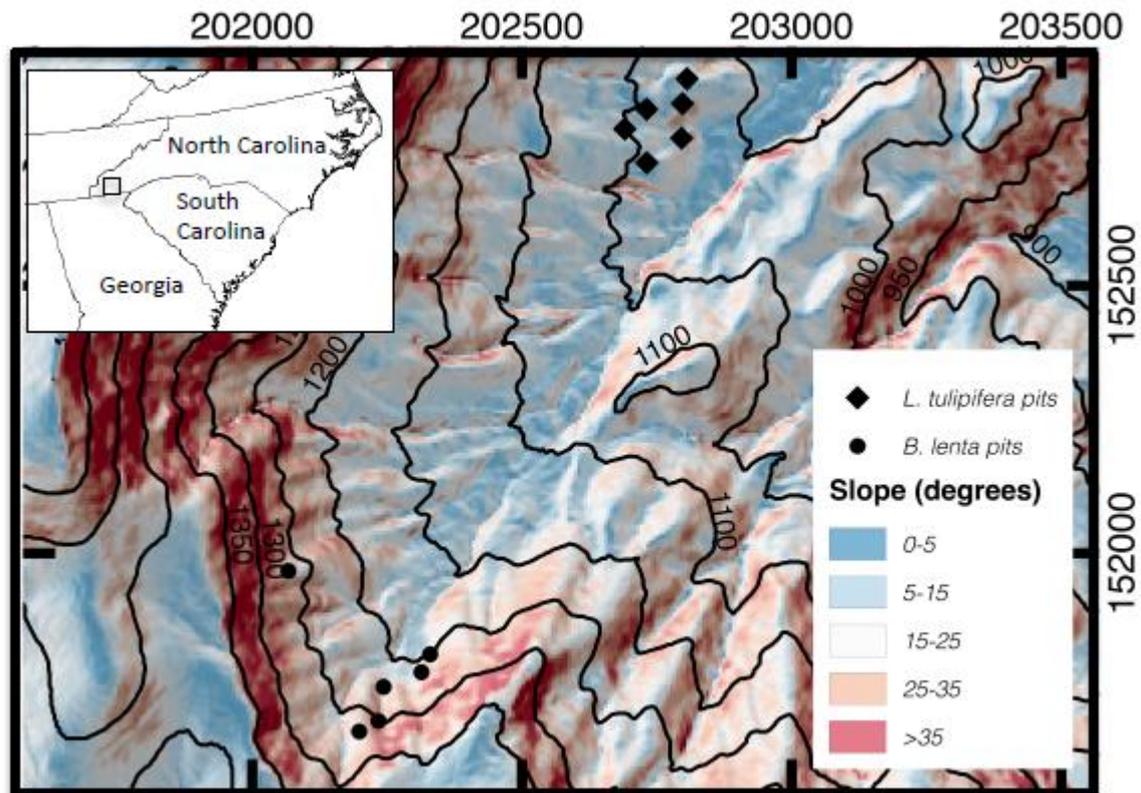


Figure 1. Map of the sampling pit locations within watershed 28 in Coweeta Hydrologic Laboratory, North Carolina, USA (inset map shows location in southeastern USA). Map shows the distribution of slopes (colour) and elevations (contours) within the catchment. *L. tulipifera* pits (diamonds) were excavated at lower elevations than *B. lenta* pits (circles). Grid units are in metres based on the North Carolina State Plane.

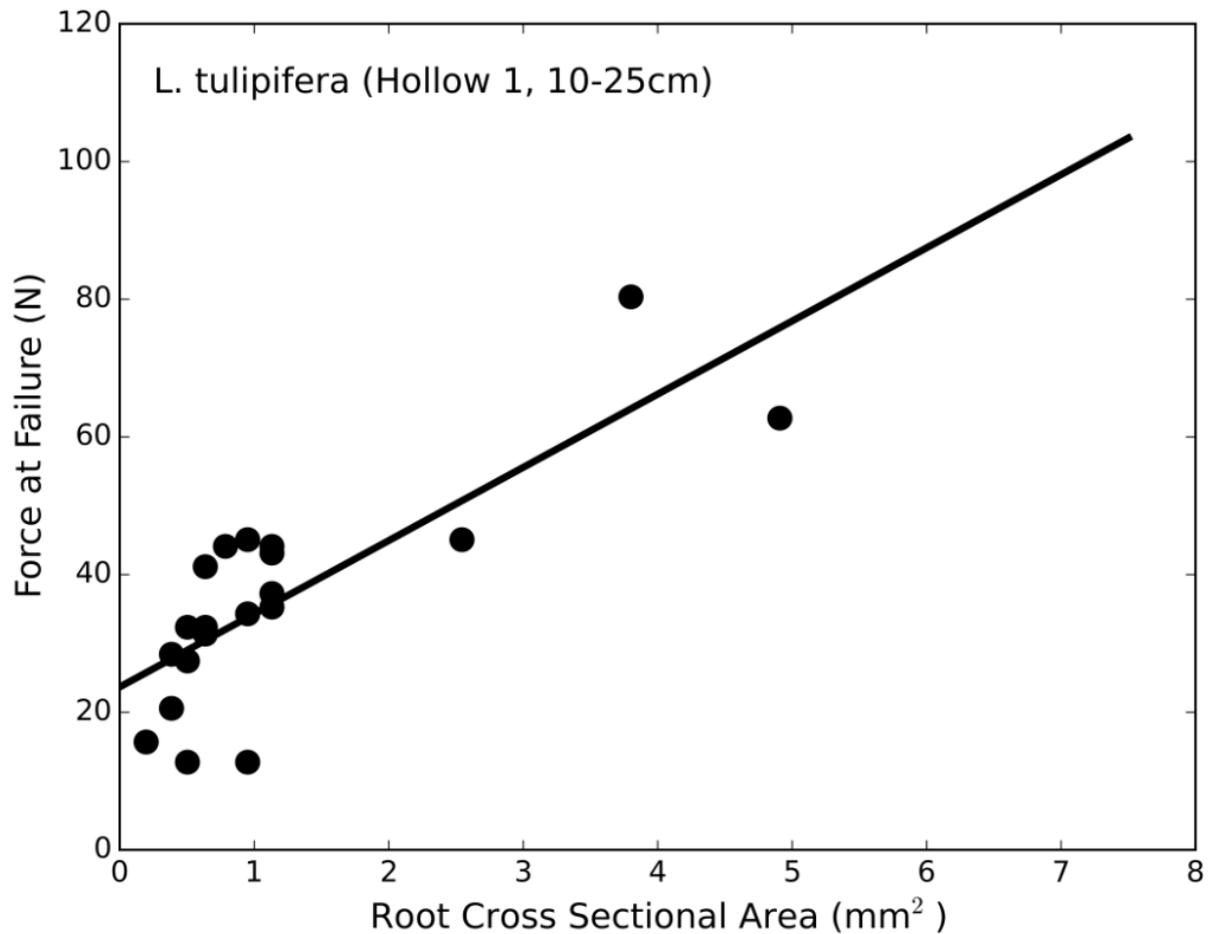


Figure 2. Plot of the relationship between root force at failure and root cross sectional area for one of our depth increments (*B. lenta*, hollow, replicate 1, depth increment 25-45cm). The plot shows the linear regression fit for these data; the slope of this line is the tensile strength of the roots for this depth increment.

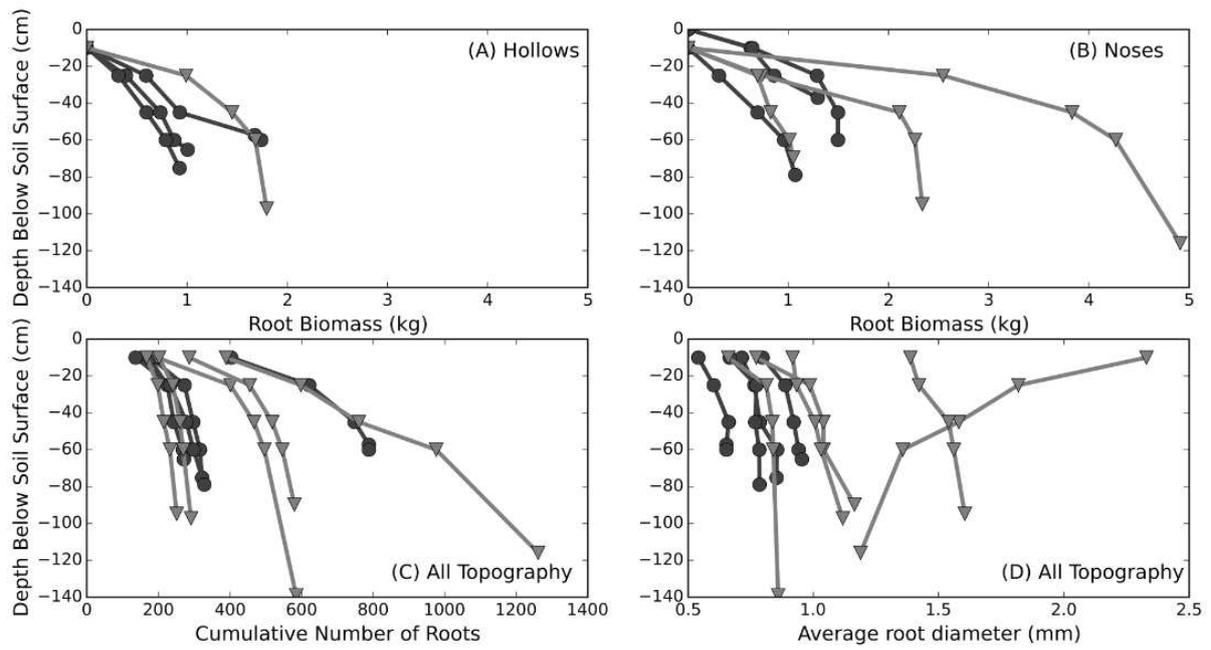


Figure 3. The depth distribution of roots and root biomass for *B. lenta* (black circles) and *L. tulipifera* (grey triangles) sites. The cumulative depth distribution of root biomass for each (A) hollow and (B) nose pit. (C) the depth distribution of root number and (D) average root diameter for all topographic locations.

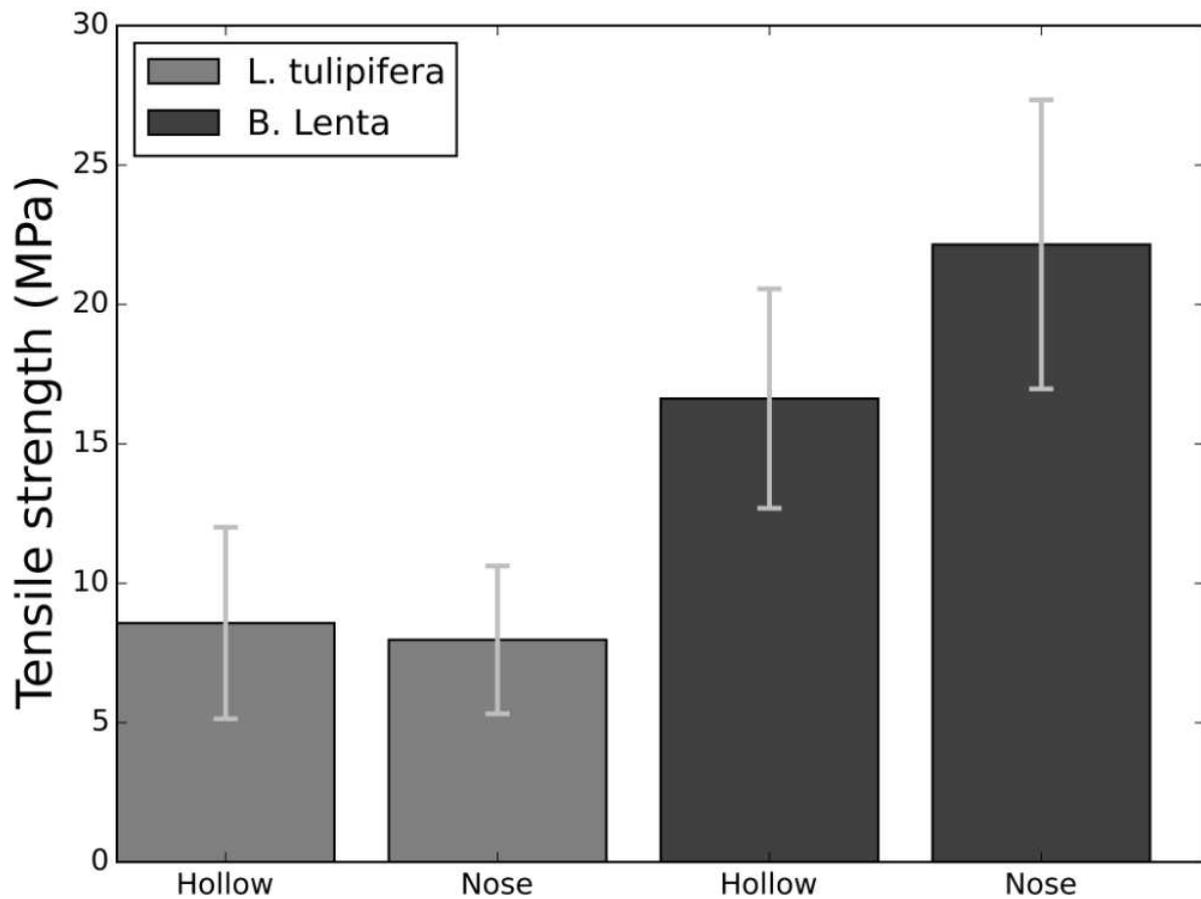


Figure 4. The relationship between species, tensile strength and topography for our sites. Mean tensile strengths for *L. tulipifera* (grey bars) and *B. lenta* (black bars) pits with error bars showing 1 standard deviation in root strength measurements for each site.

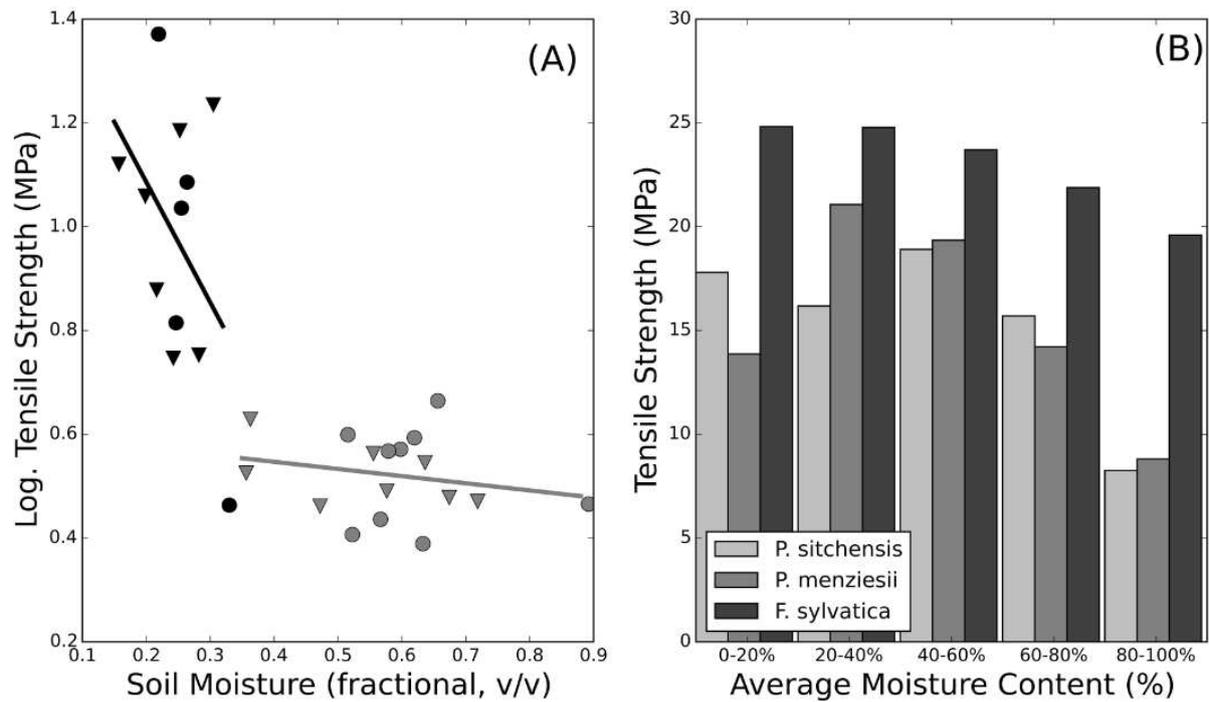


Figure 5. (A) Relationship between soil moisture content and tensile strength for our pit sites showing the relationship for the log of tensile strength against soil moisture content for *B. lenta* (black points and line) and *L. tulipifera* (grey points and line). Triangles are noses, circles are hollows. (B) Relationship between root moisture content and tensile strength for our laboratory experiment.

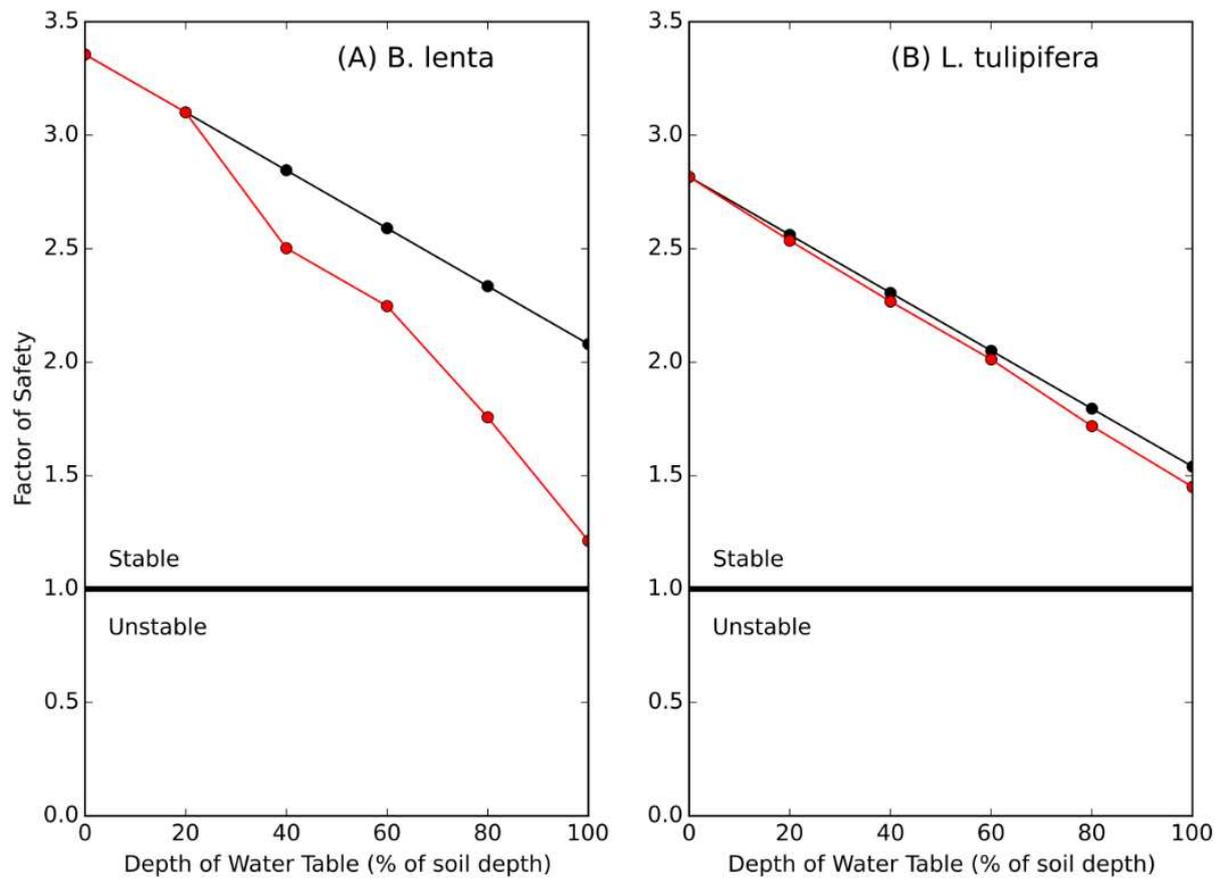


Figure 6. Predictions of slope stability for different saturated soil depths and root reinforcements for two example hollows, (A) *B. lenta* Hollow 3, and (B) *L. tulipifera* Hollow 2. For each hollow the factor of safety is calculated assuming a constant root reinforcement that is the equivalent of dry roots but varying saturated soil depth (black line) or a varying root reinforcement (red line).