Root moisture content influence on root tensile tests of herbaceous plants

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Abstract

Root tensile strength controls root reinforcement, but a range of factors including root moisture and diameter have such a large impact that it is difficult to make predictions. In this study, we measured how variable root moisture content affects the relationship between root diameter and root tensile strength of herbaceous plants. Fresh roots of two herbaceous plants, *Heteropappus altaicus* and *Poa sphondylodes* were divided into four groups: (i) saturated in water, (ii) kept fresh, (iii) or dried for 6 hours or (iv) 12 hours in air. Root diameter and mechanical failure under tension before and after the moisture treatment were measured. Tensile strength and tensile force of both species decreased linearly while mean root diameter increased linearly with increasing root moisture content. Root moisture content has a large impact on the variability of root tensile strength. This emphasizes the need to avoid desiccation during testing. In field impacts of soil water potential on root strength requires further study. We recommend soaking roots in water before testing to decrease this source of error.

Keywords

Soil reinforcement; root moisture content; root tensile strength; root diameter; herbaceous plants

Introduction

Vegetation can protect slopes from shallow landslides by mechanical reinforcement effect of the root system underground (Gray and Sotir, 1996). The type, distribution, dimension and tensile strength of roots control reinforcement (Hales et al., 2009; Loades et al., 2010; Stokes et al., 2008), with seasonal differences resulting due to root age, desiccation and soil properties (Pollen, 2007; Wynn, 2004). From investigations of the failure of roots in landslides and by conducting direct shear tests on soil columns permeated with roots, several models of root reinforcement have been developed. These include the simultaneous breakage model of perpendicular or angled roots (Waldron, 1977; Waldron and Dakessian, 1981; Wu et al., 1979), or more recently the fibre bundle model(Pollen and Simon, 2005) and the root bundle model (Schwarz et al., 2010) where roots break successively from weakest to strongest. These models need only a few parameters, usually the root tensile strength and the roots distribution and their diameters. However, the models are limited by the quality of data, especially root tensile strength that is affected by a large number of factors (Hales et al., 2013).

There are many ways to measure root tensile strength. In the field, it is usually measured by spring scales or self-assembled devices (e.g., Bischetti et al., 2005; Tosi, 2007), and in the laboratory under more controlled conditions by universal testing machines (UTM) (e.g., Ji et al., 2012; Mickovski et al., 2009; Zhang et al., 2012). Although UTM measurements are more precise and spring scales are seen as unreliable as the test speed cannot be precisely controlled, similar tensile strengths have been measured using either of these different measuring tools (Hales et al., 2013). Test speed may not be very important for testing as speeds of 10 mm/min or even 400 mm/min have been found to have no significant effect on tensile strengths (Zhang et al., 2012). In field tests, roots are pulled with one end clamped by devices and one end in soil. This is more realistic of failure conditions that would occur during a landslide than tests with a UTM, as root failure can occur through either breakage or pull-out. Breaking roots are similar to roots in laboratory tests while pull-out may be weaker than roots in laboratory tests (Pollen and Simon, 2005). The strength of pulled out roots is controlled by the friction between the root segment in soil and the surrounding soil, which is affected by changes in soil moisture content (Pollen, 2007). Roots extract water from soil when the soil is wet and desiccate when the soil is too dry (Dodd et al., 2015).

A root system is a complex 3D network that varies between plant species by age, root type, orientation, branching patterns, interface properties with soil, and diameters. All of these factors cause a large variability in root tensile strength. For an individual species, diameter significantly affects root strength, prompting diameter vs. strength relationships to be commonly used for parameterizing root reinforcement models. Smaller diameter roots are stronger than bigger roots, caused by the distribution of flaws with specimen size, the development of aerenchyma (Loades et al., 2013)and the chemical composition of the root tissues. Cellulose content (Genet et al., 2005) or lignin content (Zhang et al., 2014) are important to root strength and increase with decreasing root diameter. Root moisture content also affects the strength of tree roots (Turnmanina, 1965), with varying root moisture content with seasons driving changes in root strength, as dry roots are weaker than wet roots. Hales et al. (2013) and Yang et al. (2016) later also observed the phenomena that root tensile strength decreases with increasing root moisture content. However, the specific relationship between root tensile strength and root moisture content has not been characterized, particularly as affected by a decrease in diameter that may occur as a root desiccates. Moreover, studies to date have been limited to woody species. Diameter decreases would be expected to be greater in herbaceous species. Diameter is a key parameter in calculating root tensile strength from the tensile force and cross-sectional area. Many studies have explored how the moisture of wood affects its size. Moisture in wood takes two different forms: free water that is stored as liquid and vapour in cell cavities or vessels of the wood, and bound water that is held within the cell walls. When all free water has moved out of the cell, leaving only bound water saturating the cell walls, wood reaches what is called the fibre saturation point (FSP) (Smith, 1987). At and above the FSP, wood does not shrink or swell as it only has changes of free water. To our knowledge, there is no other research on the effects of root moisture content on root diameter of herbaceous species.

Therefore, this study aims to (1) find the relationship between root moisture and root tensile strength of two herbaceous plants, *Heteropappus altaicus* and *Poa sphondylodes*, in Northern China, (2) investigate whether root moisture affects root diameter, tensile force, and their relationship and (3) discuss how to account for variable root tensile strength under different root moisture content conditions. The research can provide a basis for understanding how soil moisture variability in time and space may affect root reinforcement of slopes in addition to developing testing approaches with fewer artefacts. Although slopes are less likely to fail when soils are dry, delayed root hydration during intense rainfall on a dry slope could diminish overall root reinforcement.

Materials and methods

Root sampling

Roots were collected from two typical herbaceous plants, *Heteropappus altaicus* and *Poa sphondylodes*, on the mountains of western Taiyuan City (37° 84′ N, 112° 46′ E), Shanxi Province, China (in the Loess Plateau where serious soil erosion is happening), in May with temperatures between 10°C and 25°C. The plants were established to control severe soil erosion in this area and are native species. The area has a typical warm and humid subtropical monsoon climate with an annual rainfall of 468 mm and an annual mean temperature of 9.5°C. The soil in this area is mainly classified as Semi-Luvisols (CRGCST (Cooperative Research Group on Chinese Soil Taxonomy), 2001).

Roots were placed with its original soil in insulated boxes above ice and taken quickly to the laboratory to keep roots fresh. In the laboratory, roots were selected from the soil carefully. Intact and straight roots were cut with scissors to 50 mm length, put in plastic bags, and then refrigerated at 4°C. Roots were selected to cover a broad range of diameters from 0.10 to 2.22 mm (*Heteropappus altaicus*) and from 0.05 to 0.23

mm (*Poa sphondylodes*), with a total of 400 roots sampled from each of the plant species. Tests on roots were finished within 7 days of sampling. To detect water content background of soil where roots sampled, soil water content by weight was measured after drying at 105°C in an oven and weighing.

Root treatments

To achieve different root moisture contents, fresh roots of the two species with a length of 50 mm were divided into four groups to be treated. The first group of roots was soaked in water to saturation (Saturation). When roots were soaked and weighed at half an hour intervals until no additional weight increase was observed, roots were regarded as saturated, which took 6 hours. The second group was kept fresh (Fresh) and stored for 6 hours before testing. The third group was air-dried for 6 hours (Dried 6h) at approximate 20°C and 30% relative humidity in a laboratory. The last group was air-dried for 12 hours (Dried 12h) in the same laboratory. Root moisture content (*RMC*) of each group was measured after drying at 105°C in an oven and weighing. Relative root moisture content (*RRMC*) was defined here as the proportion of *RMC* of roots to *RMC* of water saturated roots ($RRMC= RMC_{act}/RMC_{sat}$).

Root diameter measurement tests

Root diameter (*D*; 84 *Heteropappus altaicus* samples, 45 *Poa sphondylodes* samples) was measured using a digital vernier calliper with an accuracy of 0.01 mm. Digital callipers were used instead of microscopes as it is quicker to conduct and results are similar to microscopes so unlikely to produce systematic differences in measuring root diameter (Hales et al., 2013). Each 50 mm length root section was measured repeatedly at three positions: two points at a distance of 10 mm from the two ends and the middle point. The mean value of the three duplicates was considered as the *D*. To observe the variation of root diameter under different root moisture contents, the broad range of root diameters sampled from the field were measured at the same positions of the roots under fresh status (D_F) and treated status (D_T).

Root tensile tests

Root tensile tests were conducted using a spring dynamometer with an accuracy of 0.1 N and some auxiliary equipment including a stand and top and bottom grips. The top and bottom grips were connected to the stand and moved in direct line with each other to allow for accurate tensile displacement of the root specimen. The grip separation was set to 50 mm. Before conducting root tensile tests, root diameter was measured ($D_{observed}$) as described above. Roots breaking in 20 mm distance from the centre position were considered valid tests, because root failure near the clamps could be due to damage. The tensile strength (*T*) was calculated by dividing the maximal force required for failure (*F*) by the root cross-sectional area. From the initial batch of 400 root samples for each species and moisture treatment, between 31.5% (126 *Heteropappus altaicus* samples) and 32.0% (128 *Poa sphondylodes* samples) successful tensile tests resulted.

Data analysis

We introduced relative root diameter (RRD) to identify the difference between D_F and D_T as D_F / D_T . The mean relative root diameter (RRD_{mean}) is the average of all RRD after the water treatment,

$$RRD_{mean} = \frac{1}{n}\sum_{i=1}^{n}\frac{D_{Ti}}{D_{Fi}}$$

where n is the number of roots in a treatment, D_{Fi} is diameter of a root when fresh, and D_{Ti} is the diameter of the same root after the water treatment.

In tensile tests of plant roots, $D_{\mathrm{observ}ed}$ (after a treatment but before the tensile tests) is usually used to calculate the root tensile strength ($T_{\mathrm{observ}ed}$). In laboratory testing, roots are usually tested in fresh or dry or saturated states. The effect of root moisture on root diameter has not been explored. We investigated this effect by using root diameter of both the water treated sample and its initial fresh condition to calculate the tensile strength. We calculated the root diameter before a treatment ($D_{\mathrm{initi}al}$) by dividing $D_{\mathrm{observ}ed}$ by RRD_{mean} . Therefore, the calculated root strength $T_{\mathrm{calcul}ated}$ after a water treatment, but ignoring the change in root diameter change through desiccation, can be expressed by the following relationships:

$$D_{initial} = \frac{D_{observed}}{RRD_{mean}}$$

$$T_{observed} = \frac{F}{\frac{\pi D_{observed}^{2}}{4}}$$

$$T_{\mathrm{calcul}ated} = \frac{F}{\frac{\pi D_{initial}{}^{2}}{4}} = RRD_{mean}^{2} T_{observed}$$

The data were analysed using SPSS 16.0 for Windows (SPSS, Chicago, IL, USA). Combined with a histogram with the normal curve superimposed, a Kolmogorov-Smirnov test was initially used to test the normality of the data. Linear and power regressions were conducted to evaluate the correlations between the different variables. In the root diameter measurement tests, the differences of diameters between different treatments within the same D_F and D_T were analysed using analysis of variance (ANOVA) and Tukey's test. Differences of diameters between D_F and D_T in the same treatment were evaluated by paired-samples T tests. In the tensile tests, differences in diameter and tensile strength between measured groups ($D_{observed}$, T_{observed}) and calculated groups ($D_{initial}$, $T_{\mathrm{calculated}}$) in the same treatment were tested by paired-sample T tests. ANOVA was conducted to investigate differences of diameter among different treatments within the same measured group and calculated group. Differences in tensile force and tensile strength among different treatments within the same measured group and calculated group were evaluated using analysis of covariance (ANCOVA) with diameter as a covariate factor. T_{observed} , tensile force (*F*) and $D_{observed}$ were log-transformed. The relationship between either log(T_{observed}) or log(*F*) and log($D_{observed}$) was obtained by regression analysis, and the differences in the regression coefficients were compared among the four treatments using a General Linear Model.

Results

Soil water contents and root moisture contents

The mean water content of the topsoil (0-20 cm) where the roots sampled was 14.01%, ranging from 11.53% to 16.66% (Fig. 1). The top 10 cm soil had greater moisture than at 10 to 20 cm depth.

Relative root moisture contents of *Heteropappus altaicus* roots were smaller in the treatments of fresh and air died 12h than *Poa sphondylodes* roots (Table 1; $P<0.01$). The order of root moisture content of the two species under the four treatments followed the expected trend of Saturation>Fresh>Dried 6h>Dried 12h. Fresh roots of *Heteropappus altaicus* from the soil had a moisture content of 100.29 ± 7.30% while *Poa sphondylodes* had a moisture content of 39.36 ± 2.61% (average ± standard error). After saturation in water, root moisture content increased by 82% for *Heteropappus altaicus* and 54% for *Poa sphondylodes*. Air drying roots for 6 hours and 12 hours resulted in root moisture content decreasing by 39% and 91% for *Heteropappus altaicus,* and 51% and 69% for *Poa sphondylodes* (Table 1).

Root tensile strengths and forces

The root tensile strength (T) of *Heteropappus altaicus* and *Poa sphondylodes* decreased strongly with root diameter according to a power law, but root tensile force (F) increased with diameter according to a power law (Fig. 2, Table 2). T and F could be expressed as $T(D)=aD^{-b}$, $F(D)=\alpha D^{\beta}$, with parameters a and b, α and β species and root moisture content specific (Table 2). In addition, the determination coefficients of the equations were found to exceed 0.799, sometimes being close to 1.0 (Table 2). Root tensile strength of *Poa sphondylodes* (70-318 MPa) was much greater than *Heteropappus altaicus* (20-90 MPa), however, root tensile force of *Poa sphondylodes* (0.6-3.1 N) was less than *Heteropappus altaicus* (1-76 N). This was due to root diameter ranges, which for *Heteropappus altaicus* and *Poa sphondylodes* were significantly different (0.15-2.19 mm and 0.06-0.22 mm respectively, $P<0.01$).

Relationships between root diameter and root moisture contents

Compared to D_F, saturation increased D_T of *Heteropappus altaicus* by 6% and *Poa sphondylodes* by 9% (Table 3). Drying for 6h and 12h decreased D_T by 6% and 10% for *Heteropappus altaicus* , and 8% and 11% for *Poa sphondylodes.* Whereas D_F and D_T were significantly different ($P<0.01$) between species, for the same species, the differences were not significant except the D_T of *Poa sphondylodes* between saturation and dried 6h (Table 3). After the treatments, the relationship between relative root diameter of D_T and D_F was erratic (Fig. 3). A linear regression relationship existed between mean relative root diameter (*RRD*) and relative root moisture content (*RRMC*) for the two species (*Heteropappus altaicus*: $RRD = 0.248RRMC + 0.837$, $R^2 = 0.999$; *Poa sphondylodes*: $RRD = 0.182RRMC + 0.881$, $R^2=0.967$) (Fig. 4). The differences of D_{observed} , D_{initial} of the two species were not significant among the four treatments in the tensile tests.

Relationships between root tensile mechanics and root moisture content

The two species had a linear relationship between tensile force and relative root moisture content (*RRMC*) (*Heteropappus altaicus*: $F = -4.118RRMC + 16.970$, $R^2 = 0.966$, $P<0.05$; *Poa sphondylodes*: $F = -0.943RRMC + 2.311$, $R^2 = 0.999$, $P<0.01$) (Fig. 5). For *Heteropappus altaicus*, the differences of mean root tensile force between the water treatments were not significant, but for *Poa sphondylodes,* the differences were significant ($P<0.05$), except for the difference between dried 6h and dried 12 h (Table 5).

The differences of $T_{\mathrm{observ}ed}$ of the two species were significant among the four treatments. $T_{\mathrm{cal}culated}$ of *Heteropappus altaicus* roots under saturation and fresh treatments were significantly different from dried 6h and 12h treatments. $T_{\mathrm{cal}culated}$ of *Poa sphondylodes* roots were significantly different in all treatments except between dried 6h and dried 12 h. $T_{\mathrm{observ}ed}$ and $T_{\mathrm{cal}culated}$ were all significantly different for the two species at saturation, dried 6h and dried 12 h treatments (*P*<0.01) (Table 6). $D_{observed}$, $D_{\mathrm{init}ial}$, $T_{\mathrm{observ}ed}$ and $T_{\mathrm{cal}culated}$ of the two species all had linear relationships with the relative root moisture content (*RRMC*). However, $D_{\mathrm{init}ial}$, $T_{\mathrm{observ}ed}$ and $T_{\mathrm{cal}culated}$ decreased while $D_{observed}$ was increased with increasing *RRMC* (Fig. 6).

For each of the four treatments, log($T_{\mathrm{observ}ed}$) vs log(*D*) was negatively and log(*F*) vs log(*D*) was positively linear correlated for the two species (Tables 7). The intercepts and slopes of the linear regression equations differed significantly between treatments and plant species (Tables 7).

Discussion

Root moisture content was found to have a significant impact on the relationship between its tensile failure conditions and root diameter, with differences of >50% possible between dried and saturated roots. Even fresh roots as sampled from the field had different mechanical behaviour to saturated roots, suggesting that pre-treatment of roots by saturation to overcome the influence of seasonally variable field soil moisture should be advocated. The drivers of root moisture impacts on mechanical behaviour and the significance is discussed further below.

Effects of root moisture content on root diameter

A wide variability in root moisture content was observed between roots of the two species, *Heteropappus altaicus* and *Poa sphondylodes*, and between water treatments (Table 2), although the two species were in the soil with similar water contents in different depths (Fig. 1). This demonstrates that different plant roots may have different ability or requirement to get moisture from the soil. Guo et al. (2013) observed similar species differences in root moisture content, as well as an impact from root age, soils and seasons, but did not measure the resulting impact on root mechanics. Root moisture content clearly impacts root diameter according to our study. The linear relationship between *RRD* and *RRMC* for the two species indicates root diameter varies synchronously and linearly in response to changes in root moisture content. The change of root diameter may be similar to that of wood dimension. Researches show that shrinkage in wood begins usually below the fibre saturation point (FSP) (Smith, 1987). Certainly, the shrinkage can begin above the FSP in some circumstances (Stevens, 1963). The changes to wood dimension above the nominal FSP is attributed to the effect of hysteresis at saturation on wood properties (Hernandez and Bizon1994). The hysteresis at saturation has been described by Goulet and Hernandez (1991) as the difference between the equilibrium obtained in water desorption when starting from the FSP and that reached in desorption when starting from wood containing free water. The hysteresis may imply that loss of bound water takes place in the presence of free water.

Roots have similar structure to stem woods, containing the two main types of vascular tissue, xylem and phloem to form the stele. The stele of even herbaceous plants may have the FSP like wood, with dimensions decreasing if dried below the FSP, although experimental evidence does not yet exist. For a herbaceous root the influence of the epidermis and cortex on root diameter changes with water content could be more important. The cortex occupies the largest area of most annual roots, and also contains many intercellular spaces for aeration of roots. Its thickness can change reversibly resulting from changes in moisture content (Gall et al., 2002). The phenomenon of diurnal changes in stem diameter, that is shrinking during the day and swelling at night, in living trees is well known (Haasis, 1934), and in roots as well (Kozlowski and Winget, 1964). Root and stem diameter changes with moisture content likely occurs through swelling and shrinking of cortex tissues due to moisture variation from changes in relative humidity of the ambient air (Berry and Roderick, 2005; Gall et al., 2002) or soil water potential.

Effects of root moisture content on root tensile resistance

Tensile strength of the herbaceous plant roots declined linearly with increasing root moisture content in this study. The relationship can be attributed to root moisture content increasing root diameter and decreasing tensile force simultaneously. Cell walls determine the mechanical strength of plant roots. Declined tensile force with increasing root moisture content is usually related to the accumulation of water in the cell wall, which decreases the strength of bonds between organic polymers of the cell wall (Hales and Miniat, 2017). Similar results were seen in experiments of woody plant roots by Hales et al. (2013), who found that root strength of dry (or partially dry) roots during testing would be significantly stronger than that of fully saturated roots. Tree roots may lose 20%-50% of their dry strength when saturated (Hales and Miniat, 2017). Similarly, in stem wood, dry wood is up to twice as strong as wet wood but the relationship between wood strength and moisture content is nonlinear (Winandy and Rowell, 2013), and normally only happens below the FSP (approximately 30% moisture content) (Gerhards, 1982). Herbaceous roots may be different from wood and tree roots in the relationship between strength and moisture content because of the large proportion of cortex tissue and less vascular tissue in the roots.

In some tensile tests, roots were dried and rehydrated before tensile tests in order to achieve a homogeneity of root moisture content (e.g., Ji et al., 2012). Although this treatment can avoid variation of tensile strength due to different moisture among roots, the tensile strength measured of saturated roots is not the strength of fresh roots taken from soil. Variation in moisture content along roots (Hales et al., 2013) will also affect mechanical behaviour, which would be more likely to occur in freshly sampled roots as opposed to fresh roots that are hydrated in the laboratory to reflect the wettest conditions that may be found in the field. Landslides generally occur when soils are wet, so testing roots at an inappropriate water content could overestimate their potential for soil reinforcement under critical failure conditions. Bischetti et al. (2005) tensile tested fresh, live and saturated roots of eight woody species and found the resulting large differences in tensile strength may not estimate root reinforcement of slopes correctly. The tensile strength of completely dry roots should definitely never be used as it will likely be much greater than for fresh or saturated roots, and dry conditions do not occur in soil so are less relevant to understanding slope stabilisation. Our results suggest that root tensile strength under saturation is a good choice for evaluating root reinforcement and its influence on the factor of safety for slopes. Roots are weakest when saturated so this gives a safe margin. Live roots may not reach saturation moisture content if they are transpiring, but in very wet conditions when transpiration may be impaired and slope reinforcement by roots is most critical, this condition may be met (Hales and Miniat, 2017).

Conclusion

To investigate whether tensile strength of herbaceous plant roots is affected by root moisture content and understand the mechanisms, we tested root samples of *Heteropappus altaicus* and *Poa sphondylodes.* Our results showed that linear relationships exist between root tensile strength and root moisture content for the two herbaceous species. Increasing root moisture content decreases root tensile strength, resulting from a simultaneous decline in root maximum tensile force and increase in root diameter. Our results suggest that if a live performance of a root in soil reinforcement is not required, root tensile strength under saturation should be conducted to obtain data to estimate of root reinforcement.

Acknowledgments

We thank Qianchao Ouyang and Xiangke Lei for their support with part of the implementation of experiments, and Dr. Xiuping Liu from Institute of Genetics and Developmental Biology, Chinese Academy of Sciences for her review prior to the submission.

Funding: This study was supported by the National Natural Science Foundation of China projects (No. 31600582), China Scholarship Council (No. 201606935013), Natural Science Foundation of Shanxi Province of China (No. 201701D221224), Program for the Outstanding Innovative Teams of Higher Learning Institutions of Shanxi Province of China and the Engineering and Physical Sciences Research Council UK (EP/M019713/1).

References

Berry, S.L., Roderick, M.L., 2005. Plant-water relations and the fibre saturation point. New Phytol. 168, 25-37.

Bischetti, G.B., Chiaradia, E.A., 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 Soil 278, 11-22.

CRGCST (Cooperative Research Group on Chinese Soil Taxonomy), 2001. Chinese Soil Taxonomy. Science Press, Beijing and New York.

Dodd, I.C., Puertolas, J., Huber, K., Perez-Perez, J.G., Wright, H.R., Blackwell, M.S.A.,. 2015. The importance of soil drying and re-wetting in crop phytohormonal and nutritional responses to deficit irrigation. J. Exp. Bot. 66, 2239–2252.

Gall, R., Landolt, W., Schleppi, P., Michellod, V., Bucher, J.B., 2002. Water content and bark thickness of Norway spruce (Picea abies) stems: phloem water capacitance and xylem sap flow. Tree. Physiol. 22, 613-623.

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

Gerhards, C.C., 1982. Effect of Moisture-Content and Temperature on the Mechanical-Properties of Wood - an Analysis of Immediate Effects. Wood and Fiber 14, 4-36.

Goulet, M., Hernandez, R., 1991. Influence of Moisture Sorption on the Strength of Sugar Maple Wood in Tangential Tension. Wood Fiber. Sci. 23, 197-206.

Gray, D.H., Sotir, R.B., 1996. Biotechnical and soil bioengineering slope stabilization : a practical guide for erosion control. John Wiley & Sons, New York.

Guo, L., Lin, H., Fan, B.H., Cui, X.H., Chen, J., 2013. Impact of root water content on root biomass estimation using ground penetrating radar: evidence from forward simulations and field controlled experiments. Plant Soil 371, 503-520.

Haasis, F.W., 1934. Diametral changes in tree trunks. Carnegie Institution of Washington, Washington.

Hales, T.C., Cole-Hawthorne, C., Lovell, L., Evans, S.L., 2013. Assessing the accuracy of simple field based root strength measurements. Plant Soil 372, 553-565.

Hales, T.C., Ford, C.R., Hwang, T., Vose, J.M., Band, L.E., 2009. Topographic and ecologic controls on root reinforcement. Journal of Geophysical Research-Earth Surface 114.

Hales, T.C., Miniat, C.F., 2017. Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability. Earth. Surf. Proc. Land 32, 803-813.

Hernandez, R.E., Bizon, M., 1994. Changes in Shrinkage and Tangential Compression Strength of Sugar Maple Below and above the Fiber Saturation Point. Wood Fiber. Sci. 26, 360-369.

Ji, J.N., Kokutse, N., Genet, M., Fourcaud, T., Zhang, Z.Q., 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.

Kozlowski, T.T., Winget, C.H., 1964. Diurnal + Seasonal-Variation in Radii of Tree Stems. Ecology 45, 149-155.

Loades, K.W., Bengough, A.G., Bransby, M.F., Hallett, P.D., 2010. Planting density influence on fibrous root reinforcement of soils. Ecol. Eng. 36, 276-284.

Loades, K.W., Bengough, A.G., Bransby, M.F., Hallett, P.D., 2013. Biomechanics of nodal, seminal and lateral roots of barley: effects of diameter, waterlogging and mechanical impedance. Plant Soil 370, 407-418.

Mickovski, S.B., Hallett, P.D., Bransby, M.F., Davies, M.C.R., Sonnenberg, R., Bengough, A.G., 2009. Mechanical Reinforcement of Soil by Willow Roots: Impacts of Root Properties and Root Failure Mechanism. Soil Sci. Soc. Am. J. 73, 1276-1285.

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 Resource Research 41.

Schwarz, M., Cohen, D., Or, D., 2010. Root-soil mechanical interactions during pullout and failure of root bundles. Journal of Geophysical Research-Earth Surface 115.

Smith, H., 1987. Fiber saturation point a new definition, Stress development and degrade during wood drying, Skellefteå, pp. 30-36.

Stevens, W.C., 1963. The transverse shrinkage of wood. Forest. Prod. J. 13, 386-389.

Stokes, A., Norris, J.E., van Beek, L.P.H., Bogaard, T., Cammeraat, E., Mickovski, S.B., Jenner, A., Di Iorio, A., Fourcaud, T., 2008. How vegetation reinforces the soil on slopes. in: Stokes A, Norris J, Mickovski SB, Cammeraat E, Van Beek R, Nicoll BC, Achim A (Eds.), Slope stability and erosion control: ecotechnological solutions. Springer, New York, pp. 65-118.

Tosi, M., 2007. Root tensile strength relationships and their slope stability implications of three shrub species in the Northern Apennines (Italy). Geomorphology 87, 268-283.

Turnmanina, V., 1965. On the strength of tree roots. Bulletin of Moscow Society of Naturalists 70, 36-45.

Waldron, L.J., 1977. Shear Resistance of Root-Permeated Homogeneous and Stratified Soil. Soil Sci. Soc. Am. J. 41, 843-849.

Waldron, L.J., Dakessian, S., 1981. Soil Reinforcement by Roots - Calculation of Increased Soil Shear Resistance from Root Properties. Soil Sci. 132, 427-435.

Winandy, J.E., Rowell, R.M., 2013. Chemistry of Wood Strength. Handbook of Wood Chemistry and

Wood Composites, 2nd Edition, 413-455.

Wu, T.H., Mckinnell, W.P., Swanston, D.N., 1979. Strength of Tree Roots and Landslides on Prince-of-Wales-Island, Alaska. Can. Geotech. J. 16, 19-33.

Wynn, T.M., 2004. The effects of vegetation on streambank erosion. PhD Dissertation Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Yang, Y.J., Chen, L.H., Li, N., Zhang, Q.F., 2016. Effect of Root Moisture Content and Diameter on Root Tensile Properties. Plos One 11.

Zhang, C.B., Chen, L.H., 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.

Zhang, C.B., Chen, L.H., Jiang, J., Zhou, S., 2012. Effects of gauge length and strain rate on the tensile strength of tree roots. Trees-struct. Funct. 26, 1577-1584.

Table 1 Root moisture contents (*RMC*, % ; ±standard error) and relative root moisture contents (*RRMC*) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*).

Species	Parameters	No. of samples	Treatments			
			Saturation	Fresh	Dried 6h	Dried 12h
Heteropappus altaicus	*RMC*	3	182.44±11.09	100.29±7.30	61.23±4.35	9.36±2.02
	RRMC		1.00	0.55	0.34	0.05
Poa sphondylodes	*RMC*	3	60.45±4.66	39.36±2.61	19.27±2.06	12.31±1.57
	RRMC		1.00	0.65	0.32	0.20

Table 2 The power law relationships between observed root tensile strength ($T_{\mathrm{obser}ved}$) or tensile force at failure (*F*) and root diameter (*D*) for the two species (*Heteropappus altaicus* and *Poa sphondylodes*).

Species	Treatments	No.of roots	*F*-*D* Relationship	R^2	*T*-*D* Relationship	R^2
Heteropappus altaicus	Saturation	31	$F = 18.437D^{1.665}$	0.990	$T = 23.471D^{-0.335}$	0.799
	Fresh	35	$F = 20.266D^{1.575}$	0.989	$T = 25.804D^{-0.425}$	0.871
	Dried 6h	29	$F = 26.854D^{1.550}$	0.989	$T = 34.192D^{-0.450}$	0.880
	Dried 12h	31	$F = 28.669D^{1.504}$	0.989	$T = 36.503D^{-0.496}$	0.904
Poa sphondylodes	Saturation	37	$F = 18.312D^{1.336}$	0.982	$T = 23.311D^{-0.664}$	0.930
	Fresh	18	$F = 16.103D^{1.102}$	0.985	$T = 20.503D^{-0.898}$	0.978
	Dried 6h	38	$F = 13.726D^{0.950}$	0.870	$T = 17.477D^{-1.050}$	0.891
	Dried 12h	35	$F = 16.119D^{0.993}$	0.971	$T = 20.523D^{-1.007}$	0.972

R^2 is the coefficient of determination for the power law regressions.

Table 3 Fresh diameters (D_F , mm; ±standard error) and treated diameters (D_T , mm; ±standard error) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*) under the four root moisture treatments.

Species	Treatments	No. of roots	D_F		D_T		*P* value	RRD_{mean}
			Range	Mean	Range	Mean		
Heteropappus altaicus	Saturation	27	0.140-2.110	0.787±0.115 a	0.157-2.203	0.833±0.122 b	<0.01	1.057
	Dried 6h	27	0.110-1.857	0.769±0.111 a	0.100-1.780	0.720±0.106 b	<0.01	0.931
	Dried 12h	28	0.103-1.983	0.789±0.113 a	0.097-1.833	0.708±0.103 b	<0.01	0.890
Poa sphondylodes	Saturation	15	0.073-0.213	0.141±0.011 c	0.080-0.227	0.153±0.012 d	<0.01	1.083
	Dried 6h	15	0.060-0.200	0.132±0.011 c	0.053-0.187	0.122±0.011 e	<0.01	0.918
	Dried 12h	15	0.067-0.200	0.142±0.010 c	0.060-0.177	0.126±0.009 de	<0.01	0.884

P values indicate a significant difference between D_F and D_T at 0.05 level. The different lowercase letters in the same column indicates the differences of *D* among the three treatments for the same species.

Table 4 Observed root diameters (D_{observed} , mm; ±standard error) and calculated root diameters ($D_{initial}$, mm; ±standard error) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*) under the four root moisture treatments in the tensile tests.

Species		Treatments			
		Saturation	Fresh	Dried 6h	Dried 12h
Heteropappus altaicus	No. of roots	31	35	29	31
	D_{observed}	0.72±0.10 a	0.64±0.08 a	0.66±0.07 a	0.64±0.07 a
	$D_{initial}$	0.68±0.10 A	0.64±0.08 A	0.71±0.07 A	0.72±0.07 A
	P value	<0.01		<0.01	<0.01
Poa sphondylodes	No. of roots	37	18	38	35
	D_{observed}	0.14±0.01 a	0.13±0.01 a	0.13±0.01 a	0.13±0.01 a
	$D_{initial}$	0.13±0.01 A	0.13±0.01 A	0.14±0.01 A	0.15±0.01 A
	P value	<0.01		<0.01	<0.01

The different lowercase letters or capitals letters in the same row indicates the differences of *D* among the four treatments for the same species. *P* values indicate significant difference between D_{observed} and $D_{initial}$ for the same species at 0.05 level.

Table 5 Root tensile forces (*F*, N; ±standard error) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*) under the four root moisture treatments in the tensile tests.

Species	Treatments	No. of roots	Mean	Minimum	Maximum
Heteropappus altaicus	Saturation	31	13.03±3.03 a	0.90	75.00
	Fresh	35	14.25±3.60 a	1.30	66.10
	Dried 6h	29	15.77±2.74 a	1.90	62.30
	Dried 12h	31	16.84±3.19 a	3.40	76.20
Poa sphondylodes	Saturation	37	1.37±0.08 A	0.60	2.50
	Fresh	18	1.70±0.15 B	0.80	3.00
	Dried 6h	38	2.00±0.09 C	0.90	3.00
	Dried 12h	35	2.13±0.11 C	0.90	3.10

The different lowercase letters or capitals letters in the same column indicates the difference of *F* among the four treatments for the same species.

Table 6 Observed root tensile strengths ($T_{observed}$, MPa) and calculated root tensile strengths ($T_{calculated}$, MPa) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*) under the four root moisture treatments in the tensile tests.

Species		Treatments			
		Saturation	Fresh	Dried 6h	Dried 12h
Heteropappus altaicus	No. of roots	31	35	29	31
	$T_{observed}$	29.65±1.54 a	35.88±1.97 b	45.72±2.16 c	50.65±2.61 d
	$T_{calculated}$	33.12±1.72 A	35.88±1.97 A	39.62±1.88 B	40.12±2.07 B
	p value	<0.01		<0.01	<0.01
Poa sphondylodes	No. of roots	37	18	38	35
	$T_{observed}$	89.30±3.29 a	140.27±9.71 b	161.39±8.75 c	177.26±10.37 d
	$T_{calculated}$	104.74±3.86 A	140.27±9.71 B	135.98±7.37 BC	138.49±8.11 C
	P value	<0.01		<0.01	<0.01

The different lowercase letters or capitals letters in the same row indicates the differences of T among the four treatments for the same species. *P* values indicate significant difference between $T_{observed}$ and $T_{calculated}$ for the same species at 0.05 level.

Table 7 Coefficients of linear regression of log(T_{observed}) and log (F) on log(D_{observed}) of the four root moisture treatments.

Species	Treatments	No. of roots	log(T_{observed}) vs log(D_{observed})				R^2	log(F) vs log(D_{observed})				R^2
			A	P value	B	P value		A	P value	B	P value	
Heteropappus altaicus	Saturation	31	-0.335	0.004	1.371	<0.001	0.799	1.665	0.003	1.266	<0.001	0.990
	Fresh	35	-0.425		1.412		0.871	1.575		1.307		0.989
	Dried 6h	29	-0.450		1.534		0.880	1.550		1.429		0.989
	Dried 12h	31	-0.496		1.562		0.904	1.504		1.457		0.989
Poa sphondylodes	Saturation	37	-0.664	<0.001	1.368	<0.001	0.930	1.336	<0.001	1.263	<0.001	0.982
	Fresh	18	-0.898		1.312		0.978	1.102		1.207		0.985
	Dried 6h	38	-1.050		1.243		0.891	0.950		1.138		0.870
	Dried 12h	35	-0.989		1.327		0.973	1.011		1.222		0.974

A is the slope, B the intercept, and P values indicate significant difference at 0.05 level. T is tensile strength, F tensile force, and D root diameter. R^2 is the correlation of determination for the linear regressions.

Fig. 1

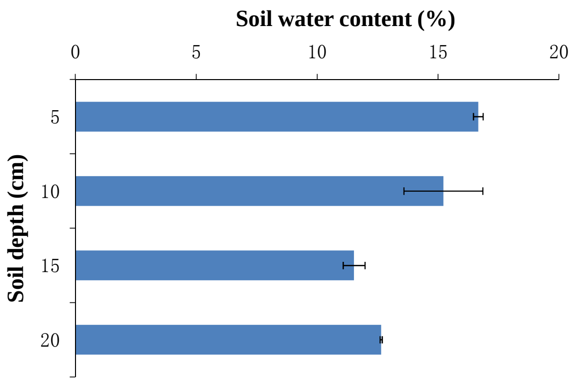
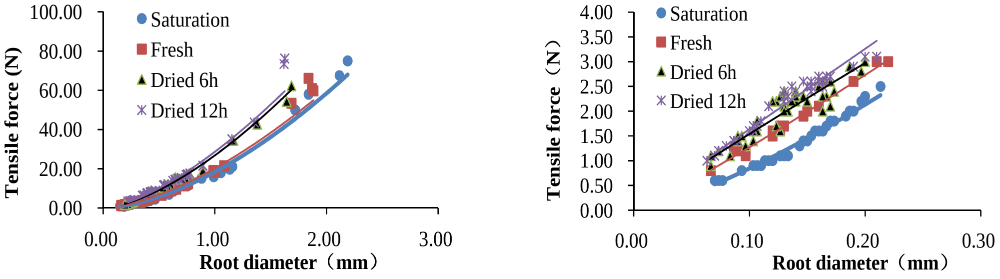


Fig. 2

Heteropappus altaicus

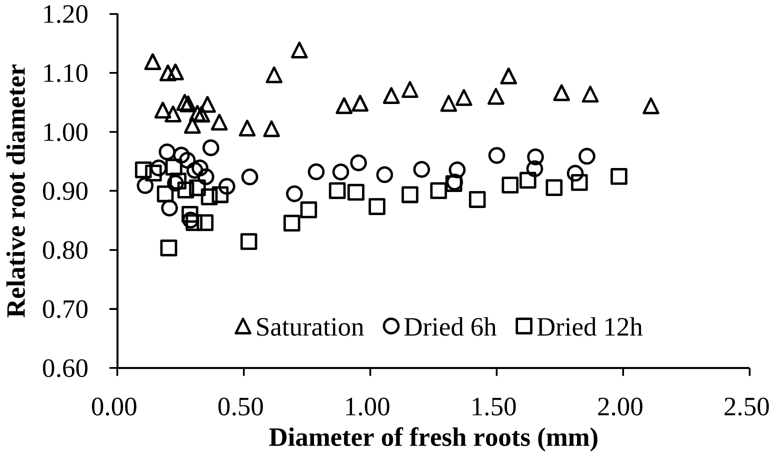
Poa sphondylodes



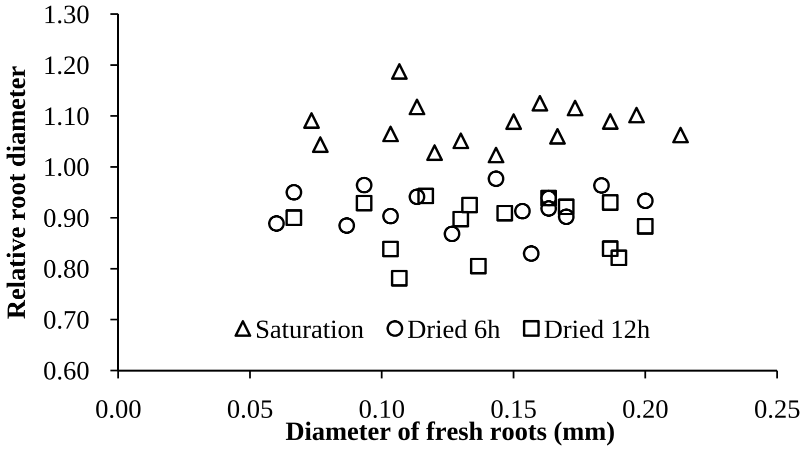
Heteropappus altaicus

Poa sphondylodes

Fig. 3



Heteropappus altaicus



Poa sphondylodes

Fig. 4

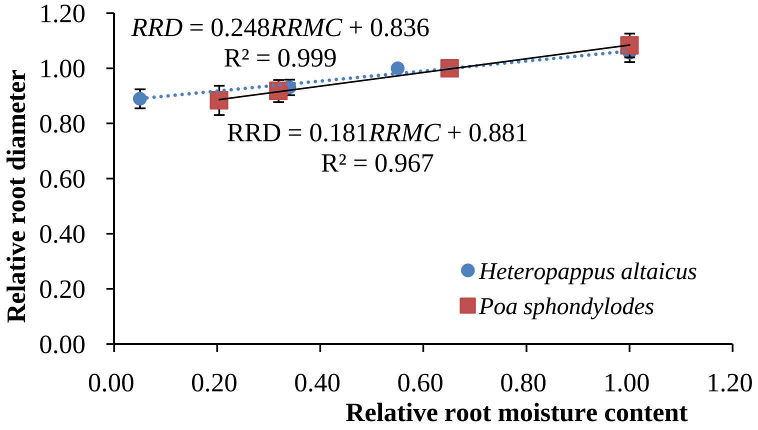
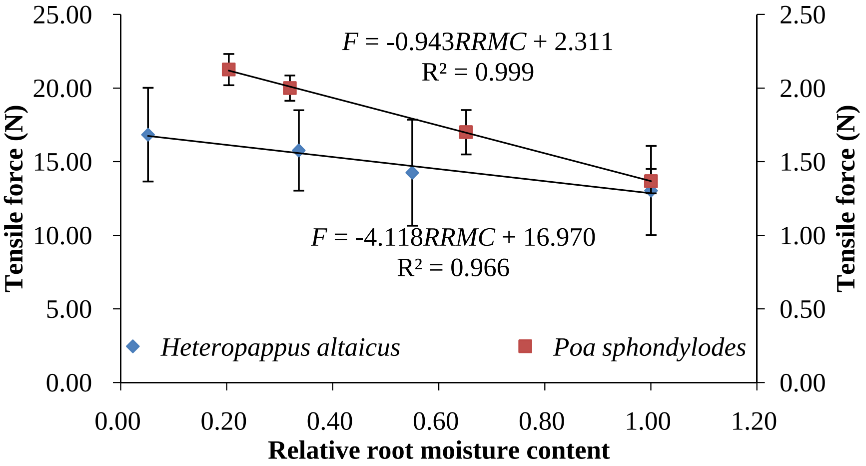
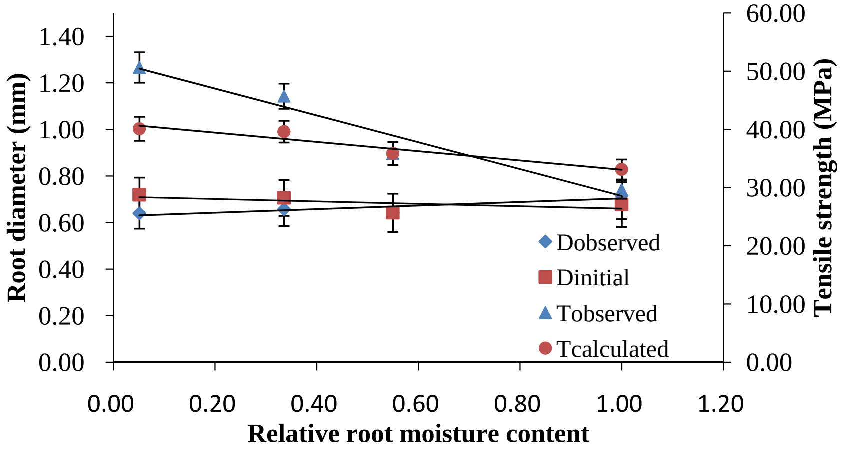

RRD = 0.248RRMC + 0.836
R² = 0.999
RRD = 0.181RRMC + 0.881
R² = 0.967
Heteropappus altaicus
Poa sphondylodes
Relative root diameter
Relative root moisture content
0.00
0.20
0.40
0.60
0.80
1.00
1.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20

Fig. 5

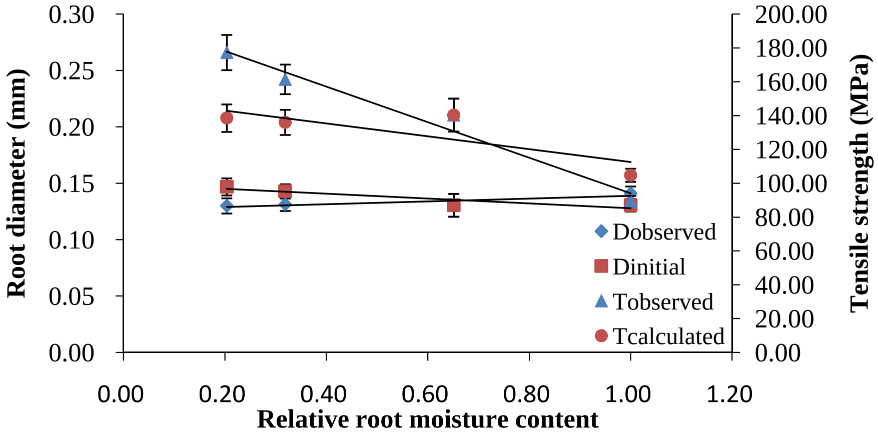


F = -0.943$RRMC$ + 2.311
R^2 = 0.999
F = -4.118$RRMC$ + 16.970
R^2 = 0.966
Tensile force (N)
25.00
20.00
15.00
10.00
5.00
0.00
Tensile force (N)
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Relative root moisture content
◆ *Heteropappus altaicus*
■ *Poa sphondylodes*

Fig. 6



Heteropappus altaicus



Poa sphondylodes

Figure captions

Fig. 1 Soil gravimetric water content at the time of sampling roots from the field. Vertical bars represent standard error of the means (SE).

Fig. 2 Relationships between root diameter and tensile strength or tensile force of the two species (*Heteropappus altaicus* and *Poa sphondylodes*). Table 1 provides details of the relationships.

Fig. 3 Relationships between relative root diameter (*RRD*) and diameter of fresh roots (D_F) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*) under three water treatments (saturation, dried 6h and dried 12h).

Fig. 4 The linear regression equations between mean relative root diameter (*RRD*) and relative root moisture content (*RRMC*) for the two species (*Heteropappus altaicus* and *Poa sphondylodes*). Vertical bars represent standard error of the means (SE).

Fig. 5 The linear regression relationships between root tensile force and relative root moisture content (*RRMC*) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*). Vertical bars represent standard error of the means (SE).

Fig. 6 The relationships between (observed and calculated) root tensile strength (*T*) and root diameter (*D*) and relative root moisture content (*RRMC*) of the two species (*Heteropappus altaicus* and *Poa sphondylodes*). Vertical bars represent standard error of the means (SE).