Detachment Characteristics of Root-Permeated Soils from Laboratory Jet Erosion Tests

Abstract

The influence of vegetation on flow and sediment dynamics at various spatial and temporal scales has been well documented. Vegetation may be one of the most effective measures in streambank stabilization. Traditionally, research on the influence of vegetation roots on streambank stabilization has focused on mechanical reinforcement and reduced applied shear stress due to above ground biomass. Few studies have investigated the effect of roots on fluvial detachment of sediment. This study conducted 36 mini-jet erosion tests (mini-JETs) on bare soil samples and 29 mini-JETs on root-permeated soil samples (average root diameters of 0.5 to 1.7 mm) to determine the role of roots in erosion resistance. The research also estimated parameters of the linear excess shear stress model (erodibility coefficient, k_d , and critical shear stress, τ_c) and a nonlinear detachment model called the Wilson Model (b_0 and b_1) and investigated the correlations between parameters of the two models and root characteristics. Root-permeated soil samples were more erosion resistant at higher shear stress as the τ_c and b_1 parameters were on average higher for the vegetated samples than the bare soil samples. As root diameter increased in the soil samples, erosion rates at high shear stress decreased. The erodibility coefficient parameters (b_0 and k_d) of both the linear and nonlinear detachment models were negatively and significantly correlated to root diameter through power functions. No significant correlation was detected between critical shear stress or b_1 and root parameters which supports conclusions of previous studies. Significant correlations were observed among the parameters of the excess shear stress model and the nonlinear detachment model; especially high correlation was observed between τ_c and b_1 for the vegetated samples. In conclusion, root-permeated soils exhibited lower erosion rates primarily through increasing the required shear stress before detachment.

Keywords: Jet erosion test; Root-permeated soils; Soil erosion; Vegetation

Introduction

A delicate feedback exists between riparian vegetation and fluvial systems which determines the form and function of the fluvial environment (Reinhardt et al., 2010; Darby, 2010; Gurnell, 2013). The influence of vegetation on flow and sediment dynamics at various spatial and temporal scales has been well documented (Curran and Hession, 2013), and determines the stability of the banks and supply of sediment load in the river (Lawler 2008, Wynn and Mostaghimi, 2006a,b). Streambank erosion, a natural process (Florsheim et al., 2008) can be intensified by various anthropogenic activities (Goodwin et al., 1997; Trimble, 1997; Belsky et al., 1999). Excess sediment loads can lead to significant impairment of natural river channels (Simon et al., 2000; Fox and Wilson, 2010). Recent restoration efforts have focused on bank stabilization to mitigate such detrimental effects (Bernhardt et al., 2005; Palmer et al. 2005).

Vegetation may be one of the most effective measures in streambank stabilization (Thorne, 1982; Simon and Darby, 1999). The above ground biomass intercepts the precipitation and protects the soil from detachment on impact (Osborn, 1954), adds to the roughness and resistance against flow, and alters the velocity profile and shear stress patterns (Curran and Hession, 2013). Loss of soil due to splash and rill erosion has been observed to decrease exponentially with percentage of vegetation cover (Poesen et al., 1994). In channelized flow, above-ground biomass reduces the near-surface velocity and applied shear stress (Millar, 2000). Roots exert significant control on the subsurface moisture condition of the streambanks, create and maintain macropores and determine seasonal variations in pore water pressure and matric

suction of soil (Pollen-Bankhead and Simon, 2010). Vegetation roots are known to have a wide range of influence on various intrinsic properties of soil such as bulk density (Lipiec, 1990), aggregate stability (Amezket, 1999), infiltration capacity, and shear strength (Gray and Sotir, 1996).

Mechanical Reinforcement by Roots

Traditionally, the focus of utilizing vegetation in hillslope and streambank stabilization has been on bio-mechanical reinforcement of the roots. As roots are strong in tension, roots act similar to steel reinforcement in concrete structures and provide resistance against shear (Waldron, 1977; Wu et al., 1979; Gray and Leiser, 1982; Anderson and Richards, 1987; Simon and Collison, 2002). The bio-mechanical reinforcement provided by the roots was initially modeled as added shear strength in a modified form of the Coulomb equation (Waldron, 1977). It was assumed that all the roots extended vertically and provided resistance against shearing in a horizontal plane. The Coulomb equation was modified to following form:

$$S = c + \Delta S + \sigma_N \tan \phi \quad (1)$$

$$\Delta S = TS \left(\sin \theta + \cos \theta \tan \phi \right) \left(\frac{A_r}{A} \right) \quad (2)$$

where S is the shearing resistance of the soil, c is the cohesion, σ_N is the normal stress applied on shear plane, ϕ is the internal angle of friction, TS is the tensile strength of the roots and A_r/A is the ratio of root area and area of the shear plane. Gray (1974) carried out a sensitivity analysis and demonstrated that the term $(\sin \theta + \cos \theta \tan \phi)$ varied from 1.0 to 1.3 for normal angles. Wu et al. (1979) adopted a value of 1.2 to simplify equation (2):

$$\Delta S = 1.2TS \left(\frac{A_r}{A} \right) \quad (3)$$

Waldron and Dakessian (1981) suggested this equation overestimated the reinforcement provided by the roots as it assumes that all the roots in a shear plane are mobilized to their maximum strength during shearing. This overestimation was verified by various field and laboratory tests carried out by Pollen et al. (2004). Pollen and Simon (2005) and Pollen (2007) suggested using a fiber bundle model called RipRoot which assumed that roots within the soil mass have different TS . Also, the load was redistributed among the remaining intact roots. This model accounted for progressive failure of roots and was more accurate than the simple perpendicular model suggested by Wu et al. (1979). Studies have incorporated the RipRoot model in bank stabilization models like the Bank Stability and Toe Erosion Model (BSTEM) to investigate the contribution of roots to the factor of safety (Pollen-Bankhead and Simon, 2009; Polvi et al., 2014), but the influence of roots on the erodibility of streambanks is not taken into account at this time.

Resistance to Fluvial Erosion by Roots

The mass failure of streambanks can be accelerated by fluvial erosion of the bank materials (Carson and Kirby, 1972; Thorne, 1982). As noted earlier, most research has focused primarily on the role of above-ground biomass in reducing the applied shear stress (Millar, 2000), mechanical reinforcement provided by the roots, and sheet and rill erosion rather than streambank erosion. Quantification of the erosion reduction provided by specifically vegetation roots has proven to be difficult (Pollen-Bankhead and Simon, 2010). Most research on how roots influence fluvial erosion has focused on deriving statistical relationships between the particle detachment rate and specific roots traits.

For example, Gyssels et al. (2005) provided a list of studies which expressed erodibility coefficients or changes in the erodibility coefficient as a function of mean root diameter and/or root length density. However, these studies failed to develop any generic predictive models. Flume experiments have been conducted to quantify the effect of roots on fluvial erosion. Mamo and Bubenzer (2001) reported significant reduction in rill erodibility (k_r) of root-permeated soil and consequent reduction in the soil detachment rate. The critical shear stress required for detachment (τ_c) was reported to be higher for root-permeated soils.

Wynn et al. (2004) compared root densities and distributions in streambanks with herbaceous and woody riparian buffers. Streambanks with primarily herbaceous vegetation were dominated by fine roots (less than 0.5 mm diameter) while woody streambanks had larger roots. Wynn and Mostaghimi (2006a) reported the effects of soil properties, root density, and freeze-thaw cycling on the erodibility of streambanks in Virginia. While soil bulk density was reported to primarily control soil erosion rates, the density of roots also had a significant influence. Similar to Mamo and Bubenzer (2001), increases in the volume of roots with diameters between 2 and 20 mm correlated to detachment rates.

De Baets and Poesen (2010) reported results of flume experiments carried out on 192 bare and 192 root-permeated topsoil samples. The authors measured the absolute sediment detachment rate using an erodibility coefficient (k_c) which is similar to k_r in the Mamo and Bubenzer (2001) study. They developed several regression models which predicted k_c as function of root density, soil bulk density and soil moisture. They performed multiple regression analysis and developed statistical models which predicted relative sediment detachment rate, or the ratio of absolute detachment rate of bare soil and root-permeated soil, as functions of root diameter and root density along with other soil and flow properties. The authors also observed differences

in erosion reducing effects for tap versus fibrous root systems. However, model validation contained unexplained variance and called for an improved process-based model.

A similar study carried out by Burylo et.al. (2012) focused on roots of two grass species and one tree species. They also used relative sediment detachment rate and investigated a larger set of root traits including root to shoot biomass ratio, root density, root volume, root mean diameter, root length density, root surface area, specific root length, root tissue density, percentage of fine roots and tensile strength (*TS*). One-way analysis of variance, analysis of covariance, and a principle component analysis identified mean root diameter (direct relationship) and percentage of fine roots with diameters less than 0.5 mm (inverse relationship) to be most influential on the relative sediment detachment rate. Therefore, their study implied that grass species with smaller mean root diameters and a higher percentage of finer roots more resisted erosion.

Cohesive Soil Detachment Models

Previous studies have called for a more mechanistic and process-based approach to quantify the detachment-reducing effects of roots (De Baets and Poesen., 2010; Burylo et al., 2012). Erodibility equations provide a more process-based approach to estimate soil detachment rates as compared to empirically-based equations or simple adjustment factors for the presence of vegetation. The most frequently used erodibility model is known as the excess shear stress equation (Partheniades, 1965). This model states that the erosion rate (ε_r , cm s⁻¹) is proportional to the difference between the applied shear stress (τ , Pa) and the critical shear stress (τ_c , Pa):

$$\varepsilon_r = k_d (\tau - \tau_c)^a \quad (4)$$

where k_d is the coefficient of erodibility ($\text{cm}^3 \text{N}^{-1} \text{s}^{-1}$) and a is an exponent usually assumed to be one (Hanson et al., 2002; Khanal et al., 2016a). The τ_c is the minimum stress required to initiate particle detachment. The k_d and τ_c are collectively called the erodibility parameters.

The model parameters (k_d , τ_c) can be estimated experimentally using various techniques like flumes, hole erosion tests and jet erosions tests (JETs). The JET is a technique used in studying the erosion properties of a soil specimen. It was developed by the USDA-ARS in Stillwater, OK (Hanson et al., 1990). The apparatus, general test methodology and procedure to analyze the data for obtaining erodibility parameters of the excess shear stress equation is described in detail by Hanson and Cook (2004). A jet of water generated by a constant pressure impinges on a soil surface in submerged conditions. The JET exerts a certain shear force on the soil surface creating a scour hole. The depth of the scour hole is measured periodically and recorded. This observed data is then fit to equation (4) to estimate the respective erodibility parameters. There are three approaches in analyzing data from JETs to estimate the erodibility parameters of the excess shear stress equation. The most popular method of analysis, called Blaisdell's solution (BL), was described by Hanson and Cook (1997) and Hanson and Cook (2004). The solution method was based on principles of fluid diffusion presented by Stein and Nett (1997) and a hyperbolic-logarithmic function modeling the progression of the scour hole depth developed by Blaisdell et al. (1981). Alternatives to the BL solution have been suggested recently (Simon et al., 2010; Daly et al., 2013). One of these solution methods is called the scour depth solution (SD). This method simultaneously searches for k_d and τ_c which provide the least squared deviation between the observed erosion rate and the erosion rate predicted by equation (4). The other approach was presented by Simon et al. (2010), and was referred to as the iterative solution (IT). Further details on this method were described by Khanal et al. (2016a).

Two versions of JETs are most commonly used: the original JET and the mini-JET. The mini-JET is the miniaturized version of the original JET apparatus. The use of mini-JET device was first described by Simon et al. (2010). A comparative study of the original JET and mini-JET devices in laboratory conditions was later conducted by Al-Madhhachi et.al. (2013a). The study concluded that, with an adjustment coefficient applied to the equilibrium depth of the “mini” JET to account for the difference in size of the nozzles of the two JET devices, original JETs and mini-JETs provided equivalent measures of the erodibility coefficients. Al-Madhhachi et al. (2013b) demonstrated that mini-JETs provided statistically equivalent measures of erodibility parameters as compared to flume tests.

Another approach to estimate the sediment detachment rate is a mechanistic model called Wilson’s model (Wilson, 1993a, 1993b), developed to predict detachment of cohesive soil particles or aggregates on the basis of the balance of forces and moments which drive and resist detachment:

$$\varepsilon_r = b_0 \sqrt{\tau} \left[1 - \exp \left\{ - \exp \left(3 - \frac{b_1}{\tau} \right) \right\} \right] \quad (5)$$

where Wilson’s model has two mechanistically-defined parameters: b_0 ($\text{gm}^{-1}\text{s}^{-1}\text{N}^{-0.5}$) and b_1 (Pa). In model evaluation studies, the nonlinear detachment model predicted detachment as well as or better than the excess shear stress equation (Wilson, 1993b; Al-Madhhachi et al., 2013b; Khanal et al., 2016a). Al-Madhhachi et al. (2013b) incorporated the hydraulics of both the original and mini-JET device into Wilson’s model and demonstrated that the parameters of Wilson’s model can also be determined from the experimental data obtained from the JETs. The observed particle detachment rate data was fit to equation (5) by minimizing the sum of squared differences between the observed and predicted scour depth.

Objectives

The JET has proven to be popular for investigating the erosion properties of soil *in situ* (Hanson and Simon, 2001; Wynn and Mostaghimi, 2006a; Simon et al., 2010; Midgley et al., 2012; Daly et al., 2015). The JET has also been employed in laboratory settings on remolded samples to investigate the effects of soil properties such as compaction moisture content and density. However, there are limited studies which have conducted JETs on root-permeated soils. Pollen-Bankhead and Simon (2010) carried out 20 JETs on root-permeated soil in a switch grass plot using the original JET device. The authors reported power relationships between the volume of the scour hole and root volume, root length density and root biomass. The study demonstrated that JETs can be used to illustrate the influence of roots on sediment scouring. However, they did not report parameters of erodibility equations and their correlation with root properties.

It was hypothesized that the erosion characteristics of root-permeated soils could be distinguished from bare soil both in terms of the fundamental erosion processes and parameters of linear and nonlinear erodibility equations. Specific objectives were as follows: (i) demonstrate significant differences in the erodibility coefficients of root-permeated soil versus bare soil; (2) investigate the correlations between erodibility coefficients of linear and nonlinear sediment detachment models; and (3) investigate the correlations between root characteristics and erodibility coefficients.

Methods and Materials

Mini-JETs were conducted in the laboratory. Soil was obtained in bulk from banks of Cow Creek in Stillwater, Oklahoma. It was air dried and sieved through a no. 4 sieve (4.75 mm).

The particle size distribution of the soil was analyzed following ASTM standard D422. Liquid limit and plastic limit of the soil were performed following ASTM standard D4318. Standard compaction tests were performed on the soils using ASTM standard D698A (ASTM, 2006) to determine a maximum density and optimum moisture content.

Samples were prepared by compacting the soil in standard proctor molds (10 cm diameter, 12.7 cm height, and 1000 cm³ volume) at constant moisture content of 10% and dry density of 1.5 Mg m⁻³. The dry density was selected below the maximum density to ensure the opportunity for root development and penetration throughout the sample; the moisture content was selected for ease in obtaining equivalent compaction conditions in the samples. The samples were tested in four batches. In each batch, a few molds were left bare and remaining molds were vegetated with seeds of Sprangletop grass (*Leptochloa dubia*). Sprangletop is grass species native to Oklahoma and has been used previously in streambank restoration projects (Lovern et al., 2013). The seeds were sown in the periphery of the samples as the middle was left bare at the surface for conducting JETs. Different numbers of seeds were sown in each vegetated sample in various patterns to achieve variable root densities (Figure 1). The samples were then placed in a greenhouse to allow the grass to grow for various time periods to ensure root penetration through the soil samples and root development. The bare samples were placed alongside the vegetated samples so that they were subjected to the same environmental conditions. The samples were watered twice a week. The amount of applied water was the same for all samples. The growing period of each batch was different based on the decision to perform the erodibility test when the roots fully penetrated through the soil samples.

Once the roots penetrated through the bottom of the molds, the above-ground biomass was then cutoff at the soil surface in order to not disturb the hydraulics of the submerged JETs.

The roots were recovered from the vegetated samples by washing and sieving after the JETs. The recovered roots were scanned using WinRHIZOTM (Regents Instruments Inc., Canada) software to determine average root diameter (D), total root length (L), root surface area (SA) and root volume (RV). The percentages of total length (FL), surface area (FSA) and volume (FV) of roots with less than 0.5 mm diameter were determined as fine root traits (Zobel, 2003; Burylo et al., 2012). Examples of the scans are shown in Figure 2. Then following Burylo et al. (2012) to investigate the influence of root strength, three of the most developed root fibers based primarily on root diameter were chosen from each sample and the peak load required to break the individual fiber was measured using an INSTRON universal testing machine. The median of these three values were recorded as the peak load (PKL). The TS of the root was calculated by dividing the PKL by the average cross sectional area of the roots. The measured root characteristics are presented in Table 1.

Data from the JETs were analyzed using a spreadsheet tool developed by Daly et al (2013). The model parameters derived from BL solution were reported as k_{d-BL} and τ_{c-BL} , and model parameters derived from SD solution were reported as k_{d-SD} and τ_{c-SD} . The parameter values derived from the iterative method were not reported as they were similar in magnitude to the k_{d-SD} and τ_{c-SD} values and similar in trend to k_{d-BL} and τ_{c-BL} . The nonlinear detachment parameters, b_0 and b_1 , were determined following the procedure proposed by Al-Madhhachi et al. (2013b) and similar to the SD solution technique.

The parameters of the erodibility equations derived from all the JETs were not normally distributed based on a Shapiro-Wilk test ($p = 0.05$) performed in SigmaPlot v13 (Systat Software, Germany). The non-parametric Mann-Whitney rank sum tests were performed to determine the statistical differences in the model parameters between the bare and vegetated

samples. The Mann-Whitney rank sum test was performed on each batch of samples as well as the compiled data. The median values of each model parameter along with the interquartile range were reported. Spearman's rank order correlation coefficients (r) were calculated to investigate correlations among the erodibility parameters as well as the correlations between erodibility parameters and root traits, again calculated using SigmaPlot v13. Regression equations were also derived using nonlinear regression routines in SigmaPlot v13 with the coefficients and overall regression equation evaluated for statistical significance.

Results and Discussion

The soil used for the experimental study was 54% sand, 38% silt, and 8% clay and non-plastic. The maximum compaction density was 1.78 Mg m^{-3} with an optimum water content of 15%. Typically, this soil would be considered highly erodible, and because of the high sand content, aggregates were not observed during the erosion testing. Roots typically penetrated throughout the depth of the soil samples within a couple of months of planting. Roots grew primarily down in the samples with a mix of branching and single root fibers. The size of the mold and limited growth period did not allow for extensive branch development. Typical root morphology is shown in Figure 2. The root length, surface area, and root volumes are reported in Table 1 with respect to the unit soil volume for comparison with other studies. For example, Burylo et al. (2012) used root diameters from 0.3 to 100 mm, percent of fine roots of 48 to 91%, and root volumes of 1 to 2 cm^3 in approximately $6,000 \text{ cm}^3$ pots. Roots in this study were typically on the lower end of the root diameters and fraction of fine roots by volume as those reported by Burylo et al. (2012), but with similar total root volumes. Scour holes generated in the

samples at the end of the JETs were typically greater than 50 mm with limited deflection of the water jet by the roots.

The erodibility parameters of the samples in different batches were significantly different. Although the samples were prepared in similar conditions, the season and time period in which they were in the greenhouse differed. Although the efforts were made to maintain consistency in watering and tending of the samples, differences in the batches could be attributed to varying evolution of the internal structure of the soil samples in response to wetting/drying and temperature effects. The growing period of each batch was different based on the decision to perform the erodibility test when the roots fully penetrated through the soil samples. Hence, the Mann-Whitney rank sum test was performed on the results obtained from each batch separately (Table 2). The differences between the batches also illustrated the influence of extrinsic factors in generating a high degree of variability in the erodibility characteristics of the soil. The role of these factors can be expected to be even more dominant in natural conditions. An additional Mann-Whitney rank sum test was also performed on the combined data set (Table 2).

Root-permeated soil samples were more erosion resistant at higher shear stress. This was supported by the fact that the τ_c and b_1 values were higher for the root-permeated samples in most batches and in the combined data set (Table 2). The detachment rate when the applied shear was greater than the critical shear stress was also lower in the vegetated samples. More specifically, the k_d and b_0 values were lower for the vegetated soil in all batches except batch 3 in which the k_{d-SD} and b_0 values increased significantly ($p = 0.05$) for the vegetated soil. This was an anomalous observation. The b_0 , however, increased for the combined data set. This observation was counter-intuitive. However, variability in b_0 was observed to be higher than any other parameter, and this variability most likely obscured any difference being measured as a

response to the presence of roots. Such variability in b_0 was consistent with observations reported in other studies (Daly et al 2013; Khanal et al., 2016a,b).

Erodibility parameters of the linear and nonlinear detachment models were correlated. The k_d and τ_c derived with the two solution methodologies were significantly correlated and also to their equivalent parameters of the nonlinear detachment model (Table 3). The k_d and τ_c estimated from each solution routine were negatively correlated ($r = -0.75, -0.54$) and significant ($p < 0.01$). This is comparable to correlation trends reported by Simon et al. (2010) and Al-Madhhachi et al (2013a). The parameters of the Wilson's equation (b_0 and b_1) were not significantly correlated (Table 3).

The rate of sediment detachment at high shear stress was negatively related to the root diameter in most cases. Erodibility coefficients of the linear excess shear stress equation (k_{d-SD}) and nonlinear detachment model (b_0) were negatively and significantly correlated to the root diameter and positively and significantly correlated to finer root traits (length, FL ; surface area, FSA ; and volume, FV) (Table 4). Burylo et al. (2012) reported negative correlation between the relative detachment rate and percentage of finer roots and concluded that a higher percentage of fine roots contributed significantly to reducing soil detachment. This contradicts the observations in this study. The percentage of the finer roots decreased as the roots developed. This may explain the positive correlations between b_0 and k_d and the fine root traits. Such correlations existed because a high percentage of fine roots were indicative of less developed roots and hence higher erodibility coefficients of the soil samples. Note that previous studies such as Burylo et al. (2012) report on plant roots from a range of species with a greater range in root diameters as opposed to this study which focused on a single grass type with a limited range in root diameters; therefore, the potential exists for there to be a greater proportion of much larger roots within the

non-fine root fraction. Potentially a more valuable parameter may be the mass fraction of fine roots proportional to the total weight of all the roots. Percentages of fine roots were calculated on a volumetric basis from the WinRhizo software. Future research should consider both volume and mass percentages of fine roots.

Exploring the correlations further revealed that relationships between b_0 , k_{d-BL} , and k_{d-SD} to the root diameter were best explained by power functions (Figure 3). All coefficients and regression equations were statistically significant. This finding was consistent with other studies that correlated soil detachment rate and scour volume with root diameter (De Baets et al., 2006, 2007; Pollen-Bankhead and Simon, 2010; De Baets et al., 2014). The relationships between erodibility parameters and root diameter can be especially useful in simulating the effect of roots on fluvial erosion in process-based models such as the Water Erosion Prediction Project (WEPP), Bank Stability and Toe Erosion Model (BSTEM), and Soil and Water Assessment Tool (SWAT), as these relationships express such effects in quantitative terms.

Erodibility parameters that relate to a critical shear stress (i.e., τ_c and b_l) were not significantly correlated to any of the root traits. However, as noted earlier, these parameters were consistently higher for the root-permeated soil and the most easily distinguishing factor between the bare and root-permeated samples. This could be either due to the higher compaction of the vegetated samples or changes in soil structure due to roots. Unfortunately, we could not test the vegetated samples for the compaction or the structural stability without destroying the samples in this study. Nevertheless, this sets one of many directions towards which this study can be expanded.

The derivation of the Wilson nonlinear detachment model includes a soil cohesion term in b_o (Wilson, 1993a,b). Furthermore, Burylo et al. (2012) suggested the importance of high root surface and higher tensile strength for soil stabilization in their concentrated flow experiments. In root reinforcement models, the additional cohesion provided to the soil by the roots is a function of TS (Wu et al., 1979; Pollen, 2007). However, no significant correlations were observed between the TS of the roots and the erodibility parameters of both models. An inverse power relation was observed between the TS and D ($R^2 = 0.68$), and this observation was in agreement with similar studies (Burylo et al 2012; Adhikari et al., 2013). However, this study shows that TS of the roots may not be significant in adding resistance against particle detachment due to fluvial forces.

It should be noted that this study was limited in scale. The vegetation was grown in molds of 10 cm diameter. This restricted the growth and development of the roots limiting their size. Hence, the ranges of root traits (L , D , and SA) were limited in comparison to the natural environment. Similarly, the mini-JETs were conducted in controlled laboratory settings. Translating the findings of laboratory studies to the natural field conditions is challenging. However, a recent study has observed that JETs conducted in controlled laboratory conditions can serve as useful guides for field tests (Khanal et al., 2016b). The scope of this study was also limited to the influence of the roots on sediment detachment. However, there are other subaerial processes active in the soil matrix which may cause the soil to erode differently even with similar root distributions (Pollen-Bankhead and Simon, 2010). These processes can explain some of the variability observed in this study. For example, future studies should monitor hydrologic changes in root-permeated samples such as pore-water pressures.

Conclusions

Mini-JETs conducted in controlled laboratory conditions can be useful in detecting and quantifying the influence of the roots on erodibility parameters. Root-permeated soil samples were more erosion resistant at higher shear stress. Furthermore, as root diameter increased in the soil samples, erosion rates decreased. Significant correlations were observed among the parameters of the excess shear stress model and the Wilson's model; especially high correlation was observed between τ_c and b_l parameters for the vegetated samples. Negative and statistically significant correlations were observed between the erodibility coefficients (k_d and b_o) of both linear and nonlinear detachment models with root diameter, and best represented through power relationships. Surprisingly, the percentage of finer roots was positively correlated with these erodibility coefficients. Also, this study failed to detect a significant correlation between root characteristics and the critical shear stress of the linear detachment model or b_l of the nonlinear detachment model. Despite some limitations, results obtained in this study can prove to be useful in simulating the erodibility of root-permeated soil in process-based models as the parameters of the erodibility models can be adjusted in relation to the root properties. Continuing this study with different vegetation and soil types in larger samples may alleviate the limitations of scale. The current practice of neglecting the effect of roots on particle detachment and considering only mass stability ignores an important process. Comparisons of the impact of above-ground biomass in affecting the applied shear versus the influence of roots in limiting detachment due to that applied shear are needed.

Acknowledgements

The authors acknowledge the financial support of the Buchanan Family Trust through the Buchanan Endowed Chair and the Oklahoma Agricultural Experiment Station at Oklahoma State University. This project was also supported by National Integrated Water Quality Program Project Grant no. 2013-51130-21484 from the USDA National Institute of Food and Agriculture.

References

- Adhikari, A. R., Gautam, M. R., Yu, Z., Imada, S., and Acharya, K., 2013. Estimation of root cohesion for desert shrub species in the Lower Colorado riparian ecosystem and its potential for streambank stabilization. *Ecological Engineering* 51, 33-44.
- Al-Madhhachi, A. T., Hanson, G. J., Fox, G. A., Tyagi, A. K., and Bulut, R., 2013a. Measuring soil erodibility using a laboratory “mini” JET. *Transactions of the ASABE* 56(3), 901-910.
- Al-Madhhachi, A. T., Hanson, G. J., Fox, G. A., Tyagi, A. K., and Bulut, R., 2013b. Deriving parameters of a fundamental detachment model for cohesive soils from flume and jet erosion tests. *Transactions of the ASABE* 56(2), 489-504.
- Amezketta, E., 1999. Soil aggregate stability: a review. *Journal of Sustainable Agriculture* 14(2-3), 83-151.
- Anderson, M. G., and Richards, K. S., 1987. *Slope stability: Geotechnical Engineering and Geomorphology*. John Wiley & Sons, New York.
- ASTM, 2006. *Annual book of ASTM Standards, Section 4: Construction*. Philadelphia, PA.

400 Belsky, A., Matzke, A., and Uselman, S., 1999. Survey of livestock influences on stream and
 401 riparian ecosystems in the western United States. *Journal of Soil and Water Conservation*
 402 54(1), 419-431.

403 Bernhardt, E. S., Palmer, M., Allan, J., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton,
 404 S., Dahm, C., and Follstad-Shah, J., 2005. Synthesizing U. S. river restoration efforts.
 405 *Science* 308(5722), 636-637.

406 Blaisdell, F. W., Hebaus, G. G., and Anderson, C. L., 1981. Ultimate dimensions of local scour.
 407 *Journal of Hydraulic Division-ASCE* 107(3), 327-337.

408 Burylo, M., Rey, F., Mathys, N., and Dutoit, T., 2012. Plant root traits affecting the resistance of
 409 soils to concentrated flow erosion. *Earth Surface Processes and Landforms* 37(14), 1463-
 410 1470.

411 Carson, M. A., and Kirkby, M. J., 1972. *Hillslope Form and Process*. Cambridge University
 412 Press, Cambridge, UK.

413 Curran, J. C., and Hession, W. C., 2013. Vegetative impacts on hydraulics and sediment
 414 processes across the fluvial system. *Journal of Hydrology* 505, 364-376.

415 Daly, E. R., Fox, G. A., Al-Madhhachi, A. T., and Miller, R. B., 2013. A scour depth approach
 416 for deriving erodibility parameters from Jet Erosion Tests. *Transactions of the ASABE*
 417 56(6), 1343-1351.

418 Daly, E., Fox, G. A., Al-Madhhachi, A. T., and Storm, D. E., 2015. Variability of fluvial
 419 erodibility parameters for streambanks on a watershed scale. *Geomorphology* 231, 281-
 420 291, doi: 10.1016/j.geomorph.2014.12.016.

421 Darby, S. E., 2010. Reappraising the geomorphology-ecology link. *Earth Surface Processes and*
 422 *Landforms* 35(3), 368-371.

423 De Baets, S., and Poesen, J., 2010. Empirical models for predicting the erosion-reducing effects
 424 of plant roots during concentrated flow erosion. *Geomorphology* 118(3), 425-432.

425 De Baets, S., Poesen, J., Gyssels, G., and Knapen, A., 2006. Effects of grass roots on the
 426 erodibility of topsoils during concentrated flow. *Geomorphology* 76(1), 54-67.

427 De Baets, S., Poesen, J., Galindo-Morales, P., and Knapen, A., 2007. Impact of root architecture
 428 on the erosion-reducing potential of roots during concentrated flow. *Earth Surface
 429 Processes and Landforms* 32, 1323-1345.

430 De Baets, S., Quine, T. A., and Poesen, J., 2014. Root strategies for rill and gully erosion control.
 431 in *Root Engineering: Basic and applied concepts*. Soil Biology, Morte, A. and Varma, A.
 432 (eds), Springer-Verlag, Berlin Heidelberg, p.493.

433 Florsheim, J. L., Mount, J. F., and Chin, A., 2008. Bank erosion as a desirable attribute of rivers.
 434 *BioScience* 58(6), 519-529.

435 Fox, G. A., and Wilson, G. V., 2010. The role of subsurface flow in hillslope and stream bank
 436 erosion: a review. *Soil Science Society of America Journal* 74(1), 717-733.

437 Goodwin, C. N., Hawkins, C. P., and Kershner, J. L., 1997. Riparian restoration in the western
 438 United States: overview and perspective. *Restoration Ecology* 5(4S), 4-14.

439 Gray, D. H., 1974. Reinforcement and stabilization of soil by vegetation. *Journal of the
 440 Geotechnical Engineering Division* 100(6), 695-699.

441 Gray, D. H., and Leiser, A. T., 1982. *Biotechnical Slope Protection and Erosion Control*. Van
 442 Nostrand Reinhold Company, New York.

443 Gray, D. H., and Sotir, R. B., 1996. *Biotechnical and Soil Bioengineering Slope Stabilization: A
 444 Practical Guide for Erosion Control*. John Wiley and Sons, New York, NY.

445 Gurnell, A., 2013. Plants as river system engineers. *Earth Surface Processes and Landforms*
446 39(1), 4-25.

447 Gyssels, G., Poesen, J., Bochet, E., and Li, Y., 2005. Impact of plant roots on the resistance of
448 soils to erosion by water: a review. *Progress in Physical Geography* 29(2), 189-217.

449 Hanson, G., and Cook, K., 1997. Development of excess shear stress parameters for circular jet
450 testing. ASAE Paper, 972227. St. Joseph, Mich: ASAE.

451 Hanson, G., and Cook, K., 2004. Apparatus, test procedures, and analytical methods to measure
452 soil erodibility in situ. *Applied Engineering in Agriculture* 20(4), 455-462.

453 Hanson, G. J., Robinson, K., and Cook, K., 2002. Scour below an overfall: Part II. Prediction.
454 *Transactions of the ASAE* 45(4), 957-964.

455 Hanson, G. J., Robinson, K. M., and Temple, D. M., 1990. Pressure and stress distributions due
456 to a submerged impinging jet. *ASCE National Conf. on Hydraulic Engineering, ASCE-*
457 *EWRI*, Reston, VA, pp. 525–530.

458 Hanson, G. J., Simon, A., 2001. Erodibility of cohesive streambeds in the loess area of the
459 midwestern USA. *Hydrological Processes* 15(1), 23-28.

460 Khanal, A., Kalvon, K., Fox, G. A., and Daly, E. R., 2016a. Comparison of linear and nonlinear
461 models for cohesive sediment detachment: Rill erosion, hole erosion test, and streambank
462 erosion studies. *Journal of Hydraulic Engineering*, doi: 10.1061/(ASCE)HY.1943-
463 7900.0001147.

464 Khanal, A., Fox, G. A., and Al-Madhhachi, A. T. 2016b. Variability of erodibility parameters
465 from laboratory mini jet erosion tests. *Journal of Hydrologic Engineering*,
466 doi:10.1061/(ASCE)HE.1943-5548.0001404.

467 Lawler, D. M., 2008. Advances in the continuous monitoring of erosion and deposition
 468 dynamics: Developments and applications of the new PEEP-3T system. *Geomorphology*
 469 93(1), 17-39.

470 Lipiec, J., 1990. *Soil Physical Conditions and Plant Growth*. Blackwell Publishing Ltd., Oxford.

471 Lovern, S., Fox, G. A., and Miller, R. B., 2013. Quantifying the erodibility and geotechnical
 472 strength of cohesive alluvial soils following streambank reconstruction. *World*
 473 *Environmental and Water Resources Congress 2013: pp. 2000-2008*. doi:
 474 10.1061/9780784412947.196.

475 Mamo, M., and Bubenzer, G.D., 2001. Detachment rate, soil erodibility, and soil strength as
 476 influenced by living plant roots part I: Laboratory Study. *Transactions of the ASAE*
 477 44(5), 1167-1174. doi:10.13031/2013.6445.

478 Midgley, T., Fox, G. A., Heeren, D. M., 2012. Evaluation of the Bank Stability and Toe Erosion
 479 Model (BSTEM) for predicting lateral streambank retreat on composite streambanks.
 480 *Geomorphology* 145-146, 107-114, doi:10.1016/j.geomorph.2011.12.044.

481 Millar, R. G., 2000. Influence of bank vegetation on alluvial channel patterns. *Water Resources*
 482 *Research* 36(4), 1109-1118.

483 Osborn, B., 1954. Effectiveness of cover in reducing soil splash by raindrop impact. *Journal of*
 484 *Soil and Water Conservation* 9, 70-76.

485 Palmer, M., Bernhardt, E., Allan, J., Lake, P., Alexander, G., Brooks, S., Carr, J., Clayton, S.,
 486 Dahm, C., and Follstad Shah, J., 2005. Standards for ecologically successful river
 487 restoration. *Journal of Applied Ecology* 42(2), 208-217.

488 Partheniades, E., 1965. Erosion and deposition of cohesive soils. *Journal of the Hydraulics*
 489 *Division, ASCE* 91(1), 105-139.

490 Poesen, J., Torri, D., and Bunte, K., 1994. Effects of rock fragments on soil erosion by water at
 491 different spatial scales: a review. *Catena* 23(1), 141-166.

492 Pollen-Bankhead, N., and Simon, A., 2010. Hydrologic and hydraulic effects of riparian root
 493 networks on streambank stability: Is mechanical root-reinforcement the whole story?
 494 *Geomorphology* 116(3–4), 353-362.

495 Pollen-Bankhead, N., and Simon, A., 2009. Enhanced application of root-reinforcement
 496 algorithms for bank-stability modeling. *Earth Surface Processes and Landforms* 34(4),
 497 471-480.

498 Pollen, N., 2007. Temporal and spatial variability in root reinforcement of streambanks:
 499 accounting for soil shear strength and moisture. *Catena* 69(3), 197-205.

500 Pollen, N., and Simon, A., 2005. Estimating the mechanical effects of riparian vegetation on
 501 stream bank stability using a fiber bundle model. *Water Resources Research* 41(7),
 502 doi:10.1029/2004WR003801

503 Pollen, N., Simon, A. and Collison, A., 2004. Advances in Assessing the Mechanical and
 504 Hydrologic Effects of Riparian Vegetation on Streambank Stability, in *Riparian*
 505 *Vegetation and Fluvial Geomorphology* (eds S. J. Bennett and A. Simon), American
 506 Geophysical Union, Washington, D. C. doi: 10.1029/008WSA10.

507 Polvi, L. E., Wohl, E., and Merritt, D. M., 2014. Modeling the functional influence of vegetation
 508 type on streambank cohesion. *Earth Surface Processes and Landforms* 39(9), 1245-1258.

509 Reinhardt, L., Jerolmack, D., Cardinale, B. J., Vanacker, V., and Wright, J., 2010. Dynamic
 510 interactions of life and its landscape: feedbacks at the interface of geomorphology and
 511 ecology. *Earth Surface Processes and Landforms* 35(1), 78-101.

512 Simon, A., and Collison, A. J., 2002. Quantifying the mechanical and hydrologic effects of
 513 riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*
 514 27(5), 527-546.

515 Simon, A., Curini, A., Darby, S. E., and Langendoen, E. J., 2000. Bank and near-bank processes
 516 in an incised channel. *Geomorphology* 35(3), 193-217.

517 Simon, A., and Darby, S., 1999. The nature and significance of incised river channels, in *Incised*
 518 *River Channels: Processes, Forms, Engineering and Management*. John Wiley & Sons,
 519 Chichester, England, pp. 3-18.

520 Simon, A., Thomas, R., and Klimetz, L., 2010. Comparison and experiences with field
 521 techniques to measure critical shear stress and erodibility of cohesive deposits. *2nd Joint*
 522 *Federal Interagency Conference*, Las Vegas, NV.

523 Stein, O., and Nett, D., 1997. Impinging jet calibration of excess shear sediment detachment
 524 parameters. *Transaction of ASAE* 40(6), 1573-1580.

525 Thorne, C., 1982. Processes and mechanisms of river bank erosion. in *Gravel-Bed Rivers* Wiley
 526 Chichester, UK, pp. 227-259.

527 Trimble, S. W., 1997. Contribution of stream channel erosion to sediment yield from an
 528 urbanizing watershed. *Science* 278(5342), 1442-1444.

529 Waldron, L., 1977. The shear resistance of root-permeated homogeneous and stratified soil. *Soil*
 530 *Science Society of America Journal* 41(5), 843-849.

531 Waldron, L., and Dakessian, S., 1981. Soil reinforcement by roots: calculation of increased soil
 532 shear resistance from root properties. *Soil Science* 132(6), 427-435.

533 Wilson, B., 1993a. Development of a fundamentally based detachment model. *Transactions of*
 534 *the ASAE* 36(4), 1105-1114.

535 Wilson, B., 1993b. Evaluation of a fundamentally based detachment model. *Transactions of the*
 536 *ASAE* 36(4), 1115-1122.

537 Wu, T. H., McKinnell III, W. P., and Swanston, D. N., 1979. Strength of tree roots and
 538 landslides on Prince of Wales Island, Alaska. *Canadian Geotechnical Journal* 16(1), 19-
 539 33.

540 Wynn, T. M., and Mostaghimi, S., 2006a. The effects of vegetation and soil type on streambank
 541 erosion, southwestern Virginia, USA. *J. American Water Resources Association*
 542 42(1):69-82.

543 Wynn, T. M., and Mostaghimi, S., 2006b. Effects of riparian vegetation on stream bank subaerial
 544 processes in southwestern Virginia, USA. *Earth Surface Processes and Landforms* 31(4),
 545 399-413.

546 Wynn, T., Mostaghimi, S., Burger, J., Harpold, A., Henderson, M., and Henry, L.-A., 2004.
 547 Variation in root density along streambanks. *Journal of Environmental Quality* 33, 2030-
 548 2039.

549 Zobel, R. W. 2003. Sensitivity analysis of computer-based diameter measurement from digital
 550 images. *Crop Science* 43, 583-591. doi:10.2135/cropsci2003.5830

Table 1. Root properties obtained from the JET samples and measured by WinRHIZO.

SN*	D	L**	SA**	RV**	FL***	FSA***	FV***	PKL	TS
	mm	cm cm ⁻³	cm ² cm ⁻³	10 ⁻³ cm ³ cm ⁻³	%	%	%	N	N mm ⁻²
1	0.7	0.34	0.07	1.2	60.4	26.3	5.1		
2	0.8	0.23	0.05	1.0	55.0	22.2	4.5		
3	0.7	0.35	0.08	1.4	58.1	25.3	5.7		
4	1.0	1.32	0.43	11.2	49.7	14.0	1.0		
5	0.9	1.08	0.29	6.1	50.3	17.6	2.4		
6	1.0	1.67	0.51	12.4	46.4	13.9	1.6		
7	0.5	0.64	0.10	1.2	72.6	47.4	20.5	0.4	1.9
8	0.5	0.08	0.01	0.1	80.3	60.7	34.1	0.3	2.0
9	0.5	0.10	0.02	0.2	62.8	39.8	16.7	2.6	11.7
10	0.5	0.62	0.10	1.2	74.0	49.3	22.0	0.4	2.0
11	0.5	0.67	0.11	1.3	73.2	46.3	17.0	0.4	1.9
12	0.8	1.63	0.43	8.9	54.2	19.9	2.6	2.1	3.9
13	0.7	1.53	0.35	6.5	57.5	23.8	3.0	2.4	5.6
14	0.8	1.38	0.36	7.3	52.2	18.1	2.7	2.3	4.3
15	0.9	1.63	0.44	9.6	52.6	18.1	1.9	4.3	7.4
16	1.0	1.30	0.41	10.3	51.5	15.7	1.2	2.7	3.4
17	1.1	1.89	0.67	18.8	48.3	12.7	0.8	4.6	4.6
18	1.0	1.16	0.37	9.4	51.3	15.5	1.3	3.4	4.1
19	0.8	0.78	0.18	3.5	56.9	22.2	3.6	2.8	6.1
20	1.2	0.90	0.35	10.7	48.7	11.8	0.7	1.7	1.4
21	1.2	0.96	0.37	11.5	47.6	11.7	0.6	4.2	3.5
22	1.1	1.23	0.43	11.7	50.3	13.4	1.0	7.0	7.4
23	0.5	0.13	0.02	0.3	71.3	45.8	17.3	0.1	0.5
24	1.0	0.89	0.28	6.8	49.0	14.6	1.3	2.8	3.6
25	1.3	1.28	0.53	17.6	46.4	11.8	0.6	4.1	3.0
26	1.7	1.81	0.95	39.8	42.9	7.9	0.3	6.9	3.1
27	1.7	1.36	0.72	30.2	50.2	11.2	3.0	6.2	2.8
28	1.5	1.68	0.78	28.4	44.4	9.9	0.4	4.1	2.4
29	1.5	1.46	0.69	25.9	49.5	10.9	0.4	1.2	0.7

* SN = Test Number, D = Average diameter, L = Total length, SA = Surface area, RV = Root volume, FL = Length of fine root, FSA = Surface area of fine root, FV = volume of fine root, PKL = Peak load, TS = Tensile strength

** L, SA, and RV are reported on a unit soil volume basis

*** FL, FSA, and FV are percentages of the total length, surface area, and volume, respectively

Table 2. Results of Mann-Whitney rank sum tests for differences in median k_d ($\text{cm}^3\text{N}^{-1}\text{s}^{-1}$), τ_c (Pa), b_0 ($\text{gm}^{-1}\text{s}^{-1}\text{N}^{-0.5}$) and b_1 (Pa) parameters between the bare soil samples and vegetated samples at $\alpha = 0.05$. BL = Blaisdell Solution and SD = Scour Depth solution technique for estimation of parameters of the excess shear stress equation; IQR = interquartile range, defined as the difference between 25th and 75th percentile.

Batch No.	Growth Period (MM/DD/YY)	Parameter	Bare soil	Vegetated soil	
			Median values (IQR)		p-value
1 (n _{bare} = 6) (n _{vegetated} = 6)	06/09/13-08/16/13	k_{d-BL}	16.7 (11.1)	7.1 (2.3)	0.06
		τ_{c-BL}	0.1 (0.01)	0.3 (0.3)	0.01*
		k_{d-SD}	81.4 (56.6)	37.0 (55.0)	0.24
		τ_{c-SD}	1.7 (0.8)	2.1 (0.6)	0.02*
		b_0	197.6 (67.3)	131.0 (347.4)	0.69
		b_1	11.5 (5.0)	16.7 (8.4)	0.01*
2 (n _{bare} = 8) (n _{vegetated} = 7)	02/18/14-04/3/14	k_{d-BL}	55.5 (21.2)	45.6 (22.8)	0.15
		τ_{c-BL}	0.03 (0.04)	0.04 (0.07)	0.46
		k_{d-SD}	256.5 (124.2)	248.8 (129.3)	0.23
		τ_{c-SD}	0.9 (0.1)	1.1 (0.18)	0.02*
		b_0	593.2 (283.8)	569.4 (501.6)	0.78
		b_1	6.4 (1.2)	7.9 (2.0)	0.04*
3 (n _{bare} = 5) (n _{vegetated} = 5)	04/15/14-07/01/14	k_{d-BL}	6.5 (0.9)	6.9 (2.9)	0.79
		τ_{c-BL}	0.2 (0.1)	0.3 (0.2)	0.43
		k_{d-SD}	36.7 (13.9)	58.6 (28.9)	0.05*
		τ_{c-SD}	1.9 (0.4)	2.1 (0.3)	0.12
		b_0	197.9 (88.5)	342.6 (404.6)	0.05*
		b_1	16.1 (3.5)	18.7 (4.4)	0.17
4 (n _{bare} = 17) (n _{vegetated} = 10)	10/15/15-01/20/15	k_{d-BL}	13.8 (6.5)	12.1 (6.9)	0.20
		τ_{c-BL}	0.03 (0.03)	0.03 (0.02)	0.43
		k_{d-SD}	65.5 (25.5)	58.6 (26.6)	0.27
		τ_{c-SD}	1.2 (0.3)	1.3 (0.1)	0.28
		b_0	195.6 (74.0)	146.0 (14.8)	0.20
		b_1	8.2 (3.5)	9.15 (1.7)	0.40
Combined (n _{bare} = 36) (n _{vegetated} = 29)		k_{d-BL}	15.3 (30.1)	10.1 (16.2)	0.09
		τ_{c-BL}	0.04 (0.04)	0.05 (0.2)	0.02*
		k_{d-SD}	70.4 (66.7)	62.2 (58.8)	0.44
		τ_{c-SD}	1.2 (0.7)	1.3 (0.9)	0.01*
		b_0	205.8 (137.4)	213.6 (338.1)	0.90
		b_1	8.3 (5.1)	9.7 (9.3)	0.01*

Table 3. Statistically significant Spearman's rank order correlation coefficients (p-values) between parameters of the Wilson model (b_0 and b_1), excess shear stress equation estimated from Blaisdell's solution (k_{d-BL} and τ_{c-BL}) and from the scour depth solution (k_{d-SD} and τ_{c-SD}).

	b_0	b_1	k_{d-BL}	k_{d-SD}	τ_{c-BL}	τ_{c-SD}
b_0	1.00	-	-	-	-	-
b_1		1.00	-	-	-	-
k_{d-BL}		-0.86 (<0.01)	1.00	-	-	-
k_{d-SD}	0.73 (<0.01)	-0.49 (0.01)	0.76 (<0.01)	1.00	-	-
τ_{c-BL}		0.93 (<0.01)	-0.75 (<0.01)		1.00	-
τ_{c-SD}		0.98 (<0.01)	-0.86 (< 0.01)	-0.54 (<0.01)	0.90 (< 0.01)	1.00

Table 4. Statistically significant Spearman's rank order correlation coefficients (p-values) between parameters of the Wilson model (b_0 and b_1), excess shear stress equation estimated from Blaisdell's solution (k_{d-BL} and τ_{c-BL}) and from the scour depth solution (k_{d-SD} and τ_{c-SD}) and measured root traits.

	b_0	b_1	k_{d-BL}	k_{d-SD}	τ_{c-BL}	τ_{c-SD}
D*	-0.47 (0.01)			-0.45 (0.01)		
L						
SA						
RV				-0.38 (0.04)		
FL	0.53 (<0.01)	None	0.36 (0.05)	0.54 (<0.01)	None	None
FSA	0.49 (<0.01)			0.48 (<0.01)		
FV	0.40 (0.03)			0.39 (0.04)		
PKL			-0.50 (0.01)	-0.44 (0.04)		
TS						

* D = Average diameter, L = Total length, SA = Surface area, RV = Root volume, FL = % length of fine root, FSA = % Surface area of fine root, FV = % volume of fine root, PKL = Peak load, TS = Tensile strength

Figure 1. Samples prepared for JETs. Bare samples were used as controls.

Figure 2. Examples of scanned images of roots. These images were analyzed using WinRhizo to obtain root characteristics.

Figure 3. Nonlinear relationship between the root diameter and (a) b_0 , a parameter of Wilson's model, (b) k_d of excess shear stress equation derived from the Blaisdell's solution and (c) k_d of excess shear stress equation derived from the scour depth solution. All coefficients and overall regression models were statistically significant.