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Erodibility Parameters Derived from Jet and Flume Erosion Tests on Root-Permeated Soils

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Abstract: Flume tests and *in situ* jet erosion tests (JETs) allow for the process-based quantification of erodibility parameters of cohesive soils. In the excess shear stress model used to predict soil detachment, the critical shear stress (τ_c) corresponds to the stress at which fluvial forces can detach soil particles or aggregates and the erodibility coefficient (k_d) governs the rate at which detachment occurs when the imposed shear exceeds τ_c. The primary objective of this research was to derive and compare erodibility parameters from flume tests and JETs on various root-permeated soil samples. Based on statistical analysis, erodibility coefficients from the flume tests were typically statistically similar to those derived with JETs. In order to further determine the capability of the JET to indicate differences in erodibility of root-permeated soils, this research then performed JETs on side-by-side *in situ* soils. The JETs on root-permeated soils estimated significantly higher τ_c but insignificant differences in k_d compared to JETs on adjacent bare soil. A significant correlation was observed between exposed root surface area (TRSA) and τ_c, but no correlation between TRSA and k_d or the equilibrium scour depth was observed. More flume and JET experiments are needed to clarify the relationship between root-permeated soils and erodibility parameters, and address a wider range of average root diameters than was considered in this research.

Keywords: *critical shear stress, erodibility coefficient, jet erosion test, flume test, fluvial erosion, roots, streambank, vegetation*

The erosion rate of cohesive soils is often expressed using the excess shear stress equation:

$$\varepsilon_r = k_d (\tau - \tau_c)^a \qquad \text{(Equation 1)}$$

where ε_r (cm/s) is the erosion rate, k_d (cm^3/N-s) is the erodibility coefficient, τ (Pa) is the average hydraulic boundary shear stress, τ_c (Pa) is the critical shear stress, and a is an empirical exponent that is typically assumed to be unity (Partheniades 1965; Hanson 1990). The τ_c and k_d are collectively referred to as the erodibility parameters of a soil. Generally, k_d represents the capacity of a soil to erode; higher values indicate the soil is more erodible. The applied shear stress necessary to initiate erosion is represented by τ_c (Partheniades 1965).

Cohesive sediment detachment caused by fluvial erosion occurs when the τ applied by the hydraulic flow exceeds τ_c, the point at which erosion begins (Clark and Wynn 2007). Vegetation acts to lessen fluvial erosion of soil in two ways: by reducing τ imposed by hydraulic flow and increasing the resistive strength of soil (Gyssels et al. 2005; Pollen-Bankhead and Simon 2010; Burylo et al. 2012). Previous research has focused primarily on the role of above-ground biomass in reducing cohesive sediment detachment (e.g., Beeson and Doyle 1995; Hession et al. 2003). Research by Gyssels et al. (2005) reported an exponential decrease in fluvial erosion as either vegetative root mass or vegetative cover increased, suggesting both factors play an important role in reducing fluvial erosion (Figure 1). Gyssels et

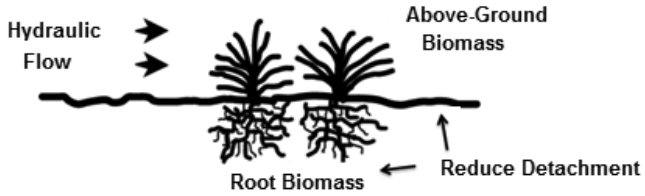

Figure 1. Vegetative cover and root networks both play a role in reducing soil detachment rates.

al. (2005) reported shallow, dense root networks characteristic of grass species as more effective than other root structure types in lessening fluvial erosion by concentrated flow. Burylo et al. (2012) argued root density alone was not sufficient in predicting the erosion-reducing effect of the root network. The vast majority of previous research investigating τ_c and k_d used an empirical approach such as simple adjustment factors of erodibility to estimate erosion in root-permeated soils. This method is limited because it fails to consider the impact of plant roots on erosion resistance and tends to underestimate τ_c (Clark and Wynn 2007).

The conventional method for deriving erodibility parameters for soils is to conduct replicated flume erosion tests in an open channel (Hanson 1990; Al-Madhhachi et al. 2013). Either disturbed and repacked or bulk samples are brought from the field, placed in the flume, and exposed to controlled flow conditions. Jet erosion tests (JETs) allow for a process-based, *in situ* determination of soil erodibility parameters (Hanson 1990; Hanson and Simon 2001). The JET impinges a stream of water through a submergence tank perpendicular to the soil surface and scours the soil, mimicking fluvial erosion caused by hydraulic flow (Hanson 1990, 1991; Hanson and Simon 2001). The depth of the resulting scour hole is recorded over gradually increasing time intervals until an equilibrium depth is reached. The applied τ is equivalent to τ_c when the scour hole reaches the equilibrium scour depth (Hanson and Simon 2001), and the time to reach the equilibrium scour depth is related to the k_d for the soil.

"Mini" JETs are smaller, more portable versions of original JETs developed by Greg Hanson in Stillwater, OK at the USDA-ARS Hydraulic Engineering Research Unit (HERU) that are more suitable for *in situ* determination of erodibility parameters. Research performed by Al-Madhhachi et al. (2013) examined erodibility parameters derived from the original and mini JET devices and reported comparable results. Using JETs specifically on root-permeated soils, Pollen-Bankhead and Simon (2010) showed that for root-permeated soils the volume of scour decreased non-linearly with an increase in root volume, root length density, and root biomass.

Research is still needed to evaluate techniques for measuring erodibility parameters of root-permeated soils and investigating the interrelation between root properties and erodibility parameters derived from JETs. In addition, a need exists to determine if JETs provide equivalent erodibility parameters as compared to the more conventional flume tests. Consequently, this study derived and compared erodibility parameters from flume tests and JETs on various root-permeated soils. It was hypothesized that flume tests performed on root-permeated soils would provide statistically similar erodibility parameters to JETs performed in similar soils. Next, side-by-side *in situ* JETs were performed on bare soils and soils near grasses with shallow, dense grass root networks. The volume of scour and rate of erosion was examined relative to measured root characteristics to determine which, if any, had an effect in reducing soil erodibility. It was hypothesized that JETs performed on soils with greater root surface area would have a shallower equilibrium scour depth, a higher τ_c, and a lower k_d than JETs in similar soils without roots.

Materials and Methods

Laboratory Flume Tests versus JETs

Ten side-by-side flume tests and JETs were conducted on root-permeated soils of two grass types: Fescue grass (*Festuca arundinacea*) and Bermuda grass (*Cynodon dactylon*). Therefore, a total of 20 erodibility tests were conducted for this part of the research. Root-permeated soil samples (25 cm wide by 25 cm long by 10 cm deep samples) were acquired from the USDA-ARS HERU grounds. Care was taken to avoid disturbance of the sample as much as possible. Adjacent samples were used for paired flume tests and JETs in an attempt to achieve similar root and soil properties between the two types of tests.

Open-channel erosion tests were conducted in a flume at the USDA-ARS HERU in Stillwater, Oklahoma. The flume consisted of the following parts: water delivery pipe, upstream water reservoir, flume channel, and a soil box. The water delivery pipe, 30.5 cm in diameter, delivered the required discharge from Lake Carl Blackwell to the water reservoir. Initial control of water supply was established in the delivery pipe with an orifice plate, a device used for measuring flow rate, reducing pressure, or restricting flow. The water reservoir was 1.2 m long, 1.2 m wide, and 1.4 m deep and provided inflow to the flume. A manometer and corresponding chart in the lab established the water height in the reservoir and flow rate for each test. The flume channel was 9 m long by 0.6 m wide and 0.6 m deep. A soil box 0.25 m long, 0.25 m wide, and 0.1 m deep was located at the center of the flume (Figure 2), and root-permeated soil samples were placed into the soil box (Figure 3).

Flows ranging from 0.056 m^3/s to 0.142 m^3/s were used to erode the soil samples. The minimum flow rate was based on trial experiments to determine when the flow rate was sufficient to initiate scour. The applied shear stress across the surface of the soil for the various flow rates was calculated following Hanson (1990) and Al-Madhhachi et al. (2014). In order to prevent excess scour caused by the introduced flow, a 25 cm by 25 cm metal square was placed on the soil surface before the initial flow began. Once a constant flow

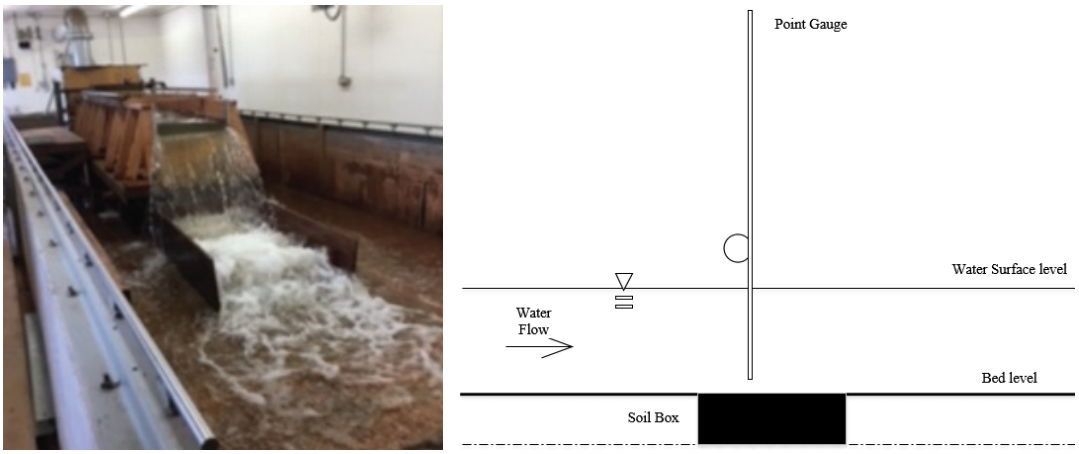

Figure 2. View of flume apparatus from below the outlet (left), and cross sectional drawing of flume apparatus at the soil box showing attached point gauge and soil sample for testing (right).

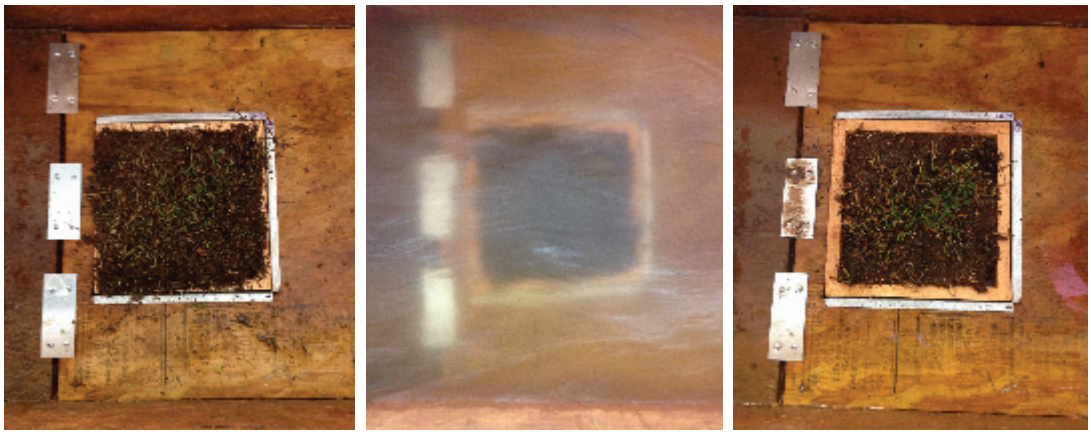

Figure 3. Soil samples positioned in the flume soil box before (left), during (middle), and after (right) hydraulic testing.

was reached, the metal square was released from the soil sample and the timer was started. The elevations of 25 points within the soil sample were measured with a point gauge before and after the test to calculate the volume of eroded soil for each flume test. In addition, during each flume test, nine points were measured around the center of the soil sample every 15 minutes for a total of 90 minutes. The water and bed surface levels were measured throughout each test.

The mini JET apparatus (Figure 4) consisted of a point gauge, rotatable plate, submergence tank, foundation ring, and jet valve. An adjustable constant head tank was used to provide the desired water head (89 cm) for the duration of the JET. The 180 mm diameter foundation ring was hammered into the surface of each soil sample. The submergence tank was positioned below the rotatable plate and point gauge, and measured 70 mm high and 101.6 mm in diameter, with a 6.4 mm wall thickness. The release of the 3.18 mm jet of water was controlled by the rotation of the brass plate, allowing scour to occur over a given time interval and preventing water from impinging on the soil at the beginning of testing and during scour depth readings (Al-Madhhachi et al. 2013). Measurements of the depth of the scour hole created by the JET were taken using a point gage and time intervals of scour were increased until the depth reading was constant, or the equilibrium scour depth was reached (Hanson 1990, 1991). The initial scour time interval for both the root-permeated and bare soil JETs began at 15 s and continued until three constant depth readings were taken. Following the standard protocol for JETs (Khanal et al. 2016), the time interval between measurements was increased to 30 s, followed by 60 s, 120 s, and 300 s, if necessary, until an equilibrium scour depth was reached and the test concluded.

The JET data were used to determine k_d and τ_c using the spreadsheet tool described by Daly et al. (2013). The JET spreadsheet tool solves for and compares variability in erodibility parameters using the Blaisdell solution, the scour depth method (Daly et al. 2013), and the iterative method (Simon et al. 2010). The Blaisdell solution remains the current standard for analyzing JET data and therefore was used as the solution technique in this research.

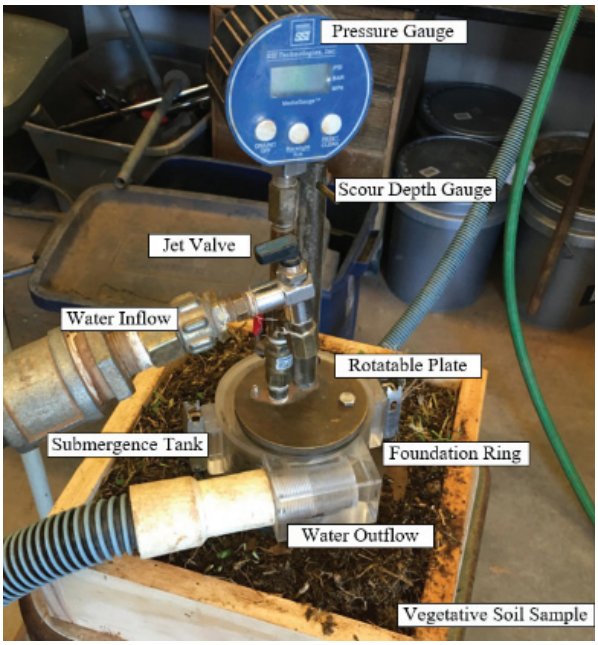

Figure 4. Mini Jet Erosion Test (JET) device installed in soil sample with important instrument components labeled. The pressure gauge shown was not utilized in the experiments.

For each of the ten paired samples, a sample 5 cm in diameter by 5 cm long was acquired to quantify bulk density, moisture content, and root characteristics. Each sample was weighed before and after 24 hours in an oven set at 105°C to obtain the bulk density and moisture content. Each sample was rinsed until only roots were present and then scanned using WinRHIZO analysis software (Regent's Instruments, Canada) (Clark and Wynn 2007). WinRHIZO scans roots lying flat in a tray of water to determine the total exposed surface area and range of root diameters.

Field Experiments: Bare versus Root-Permeated Soils

Field mini JETs were performed along Cow Creek at the Stream Restoration and Streambank Stabilization Site in Stillwater, OK. The restored reach of Cow Creek is a meander bend east of the Oklahoma State University (OSU) Botanic Garden, bounded to the north by West Virginia Avenue and to the south by Highway 51 (Lovern et al. 2013). The initial restoration activities were performed in 2011, and included the creation of a 1:1 slope stabilization research area on the

meander. Further mitigation activities in 2012 and 2013 included the establishment of a wider riparian buffer, the implementation of J-hooks, cross-vanes, and riffles, and the construction of a floodplain overflow channel and backwater constructed wetland. The research site for the JETs was on the bench of the restored meander, located between the 1:1 stabilized slope and a 2:1 vegetated slope just above the edge of Cow Creek. Lovern et al. (2013) reported the soil types located on the filled streambank of the meander as primarily loams, clay loams, and sandy clay loams. The research site was compacted during project construction and reinforced with erosion matting, with the final step being revegetation with grass seeds and native plants (Lovern et al. 2013). Three riparian grasses with relatively shallow root networks, Little bluestem (*Schizachyrium scoparium*), Bermuda grass (*Cynodon dactylon*), and Switch grass (*Panicum virgatum*), were identified on the Cow Creek meander bench. Ten sites supporting these grasses, separated from other vegetation types and next to bare, unvegetated soil, were marked with survey flags. These areas were selected to conduct 10 pairs of side-by-side JETs (20 tests total) on root-permeated and bare soils to compare erodibility parameters between the tests while holding soil type, bulk density, moisture content, and pH as constant as possible under field conditions (Figure 5).

A 5 cm diameter by 5 cm long soil sample adjacent to the JET location was collected before running the test for measurement of bulk density, and grab samples were acquired for analysis of soil texture and pH. A constant head tank was set up with the surface approximately 61 cm above the outflow of the JET device to maintain constant water pressure for the duration of the JET. Water from the OSU Botanic Garden irrigation system was directed through a garden hose to the head tank (Figure 5). The foundation ring of the JET was hammered into the soil and secured with two nails, and the JET device was attached to the base and fastened into place with two clips. For the JETs on root-permeated soil, the foundation ring was placed with the plant stems off center to ensure the impinging jet would contact soil and roots rather than stem. Grass stems were cut to approximately 1 cm above the soil surface before the test following the method of Pollen-Bankhead and Simon (2010). Outflow hoses were attached to both the head tank and the JET and directed downslope to avoid saturating the soil surrounding the JET.

The operation of the JET matched the procedures previously described. Unique to this part of the study, after each JET, the device was then disconnected from the foundation ring and residual water was allowed to runoff and infiltrate until the scour hole was empty. Water was poured into the hole from a graduated cylinder and the



Figure 5. Field JET site with side-by-side root-permeated and bare soils (left), mini JET device installed on streambank (middle), and constant head tank connected to the JET device (right).

amount recorded to obtain an approximate volume measurement of the scour hole. The foundation ring was removed and a soil corer was placed around the scour hole and hammered into the ground to collect two 91-cm^3 samples, each 5 cm in depth, of exposed roots for analysis. Roots located in the top 5 cm were referred to as the upper roots in the soil profile, and roots in the bottom 5 cm were referred to as the lower roots. Analysis of the data focused on correlations between JET variables and the upper roots due to their greater apparent influence on the results of the tests.

As noted earlier, JET data were used to derive k_d and τ_c using the spreadsheet tool described by Daly et al. (2013) with the Blaisdell solution. If the scour depth was greater than 15 mm in the first two 15 s time intervals, the data were removed from the analysis assuming that the scour depth measurements were for loosened soil created during the insertion of the foundation ring for these *in situ* soils. These first measurements typically represented only one or two of 20 to 25 total data points acquired during each of the JETs.

The root surface area and diameters were analyzed using WinRHIZO as described previously. Grab soil samples were taken to analyze the particular soil texture at each JET site. The samples were left to air dry and particle sizes were analyzed using sieves and a hydrometer following the current ASTM standards (ASTM 2002). Soil pH was measured by adding 5 g of soil from each grab sample to 15 mL of deionized (DI) water in a vial to maintain a 1:3 soil to water ratio. Samples were shaken for 1 minute to wet all soil particles and left for 20 minutes to equilibrate, then shaken for another minute. After the second equilibration period, a calibrated pH probe was placed in the mixture and upon stabilization, a reading was taken to the nearest hundredth value. The pH probe was rinsed thoroughly with DI water between each pH measurement (Smith and Doran 1996).

Statistical Analyses

Experimental data were analyzed statistically to determine the difference between paired variables. For normally distributed variables, paired t-tests were performed to determine statistical differences in means; for non-normally distributed data, a Mann Whitney Rank sum test was used to determine statistical differences in the medians. Soil, root, flume, and JET data were analyzed statistically to determine correlations between variables. Pearson product moment correlations were also performed to determine statistically significant correlations between the soil parameters, root characteristics, and erodibility parameters. All statistical tests were based on a significance level of $\alpha = 0.05$ and used SigmaPlot 13 (Systat Software, Inc., Germany).

Results and Discussion

Laboratory Flume Tests versus JETs

Comparison of images generated with WinRHIZO software indicated that samples with Fescue grass (#1 through #5) generally had smaller root surface areas (P = 0.010) and greater diameters (although not statistically different, P = 0.473) compared to samples with Bermuda grass (#6 through #10) (Table 1). It was concluded that Bermuda grass samples had denser, more fibrous root networks than the Fescue grass samples. Although the root characteristics varied between both grass types, the soil bulk densities and moisture contents for the samples were similar. Therefore, this result shows that the desired study design of varying primarily the root characteristics was achieved.

Flume data resulted in k_d values ranging from 0.1 to 6.6 cm^3/N-s and τ_c values ranging from 0.1 to 4.8 Pa. Analysis of the JET data resulted in k_d values ranging from 0.8 to 4.3 cm^3/N-s and τ_c values ranging from 0.7 to 6.4 Pa (Figure 6). An inverse relationship was observed between τ_c and k_d derived from the flume tests and JETs as reported in previous literature (Hanson and Simon 2001; Al-Madhhachi et al. 2013; Daly et al. 2013). In general, there was greater scour observed in the Fescue grass samples than for the Bermuda samples in both flumes and JETs. The denser, more fibrous root networks in the Bermuda samples, especially in the upper layers of the soil, limited detachment or scour. Such results could be useful when considering types of grasses or cover crops for erosion control, specifically when considering the influence of roots on detachment.

No significant differences were observed in the τ_c and k_d values when comparing Fescue grass samples to the Bermuda grass samples for the side-

Table 1. Soil and root characteristics from WinRHIZO analysis software for a representative sample of the soil samples used in flume tests and JETs.

Sample #	Vegetation Type	Soil Bulk Density (g/cm^3)	Soil Moisture Content (%)	Root Surface Area (cm^2)	Average Root Diameter (mm)	Root Length Per Volume (cm/m^3)	Root Volume (cm^3)
1	Fescue	1.7	24.7	300.3	1.7	5.45×10^6	12.8
2	Fescue	1.3	20.6	344.1	2.0	5.40×10^6	17.0
3	Fescue	1.5	24.4	226.2	2.5	2.75×10^6	14.4
4	Fescue	1.3	32.9	337.6	1.9	5.51×10^6	16.0
5	Fescue	1.3	32.1	401.1	2.4	5.12×10^6	24.3
6	Bermuda	1.1	15.9	464.7	2.6	5.43×10^6	30.7
7	Bermuda	1.0	21.9	455.5	1.8	7.98×10^6	20.1
8	Bermuda	1.2	20.1	343.6	1.6	6.53×10^6	14.0
9	Bermuda	1.0	29.6	467.0	1.6	8.93×10^6	18.9
10	Bermuda	1.3	32.1	423.9	1.5	8.47×10^6	16.4

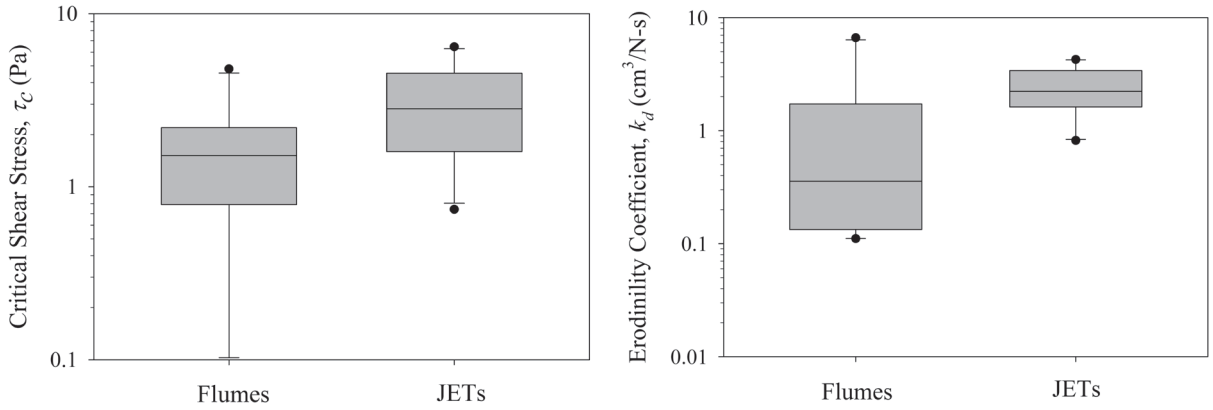

Figure 6. Box plots comparing the distribution of critical shear stress (τ_c) and the erodibility coefficient (k_d) derived from the flume tests and JETs. The mean is indicated by the solid line within the box.

by-side flume tests and JETs (Table 2). Significant differences were observed in τ_c when comparing the flume tests to the JETs across both grass types (Table 3), but not for the Fescue samples alone (Table 3). No significant differences were observed in k_d when comparing the JETs to the flume for either vegetation type or when considering both grass types together. Al-Madhhachi et al. (2013) reported no significant differences in both k_d and τ_c between the flume and JETs for bare soil samples when analyzed with the Blaisdell solution after applying a correction factor to account for differences in the equilibrium scour hole depth. No correction factor was applied in this study. Therefore, this research provides further support for the use of the JET as an appropriate tool for *in situ* and/or laboratory erodibility characterization.

While the majority of the side-by-side flume test and JET comparisons reported no statistically significant differences in the derived erodibility parameters, it should still be pointed out that differences exist in the operation of the flume tests and JETs; for example, the direction of the hydraulic flow between the flume and JETs differed.

Table 2. Results of statistical analysis of flume tests versus jet erosion test (JET) erodibility parameters for Bermuda and Fescue grass samples. For all tests $\alpha = 0.05$.

Comparisons	P-Value	Significant
τ_c *Flume Fescue* vs. τ_c *Flume Bermuda*	0.166	No
τ_c *JET Fescue* vs. τ_c *JET Bermuda*	0.056	No
k_d *Flume Fescue* vs. k_d *Flume Bermuda*	0.625	No
k_d *JET Fescue* vs k_d *JET Bermuda*	0.679	No

Table 3. Results of statistical analysis of flume tests versus jet erosion test (JET) erodibility parameters. For all tests $\alpha = 0.05$.

Comparisons	Vegetation Type	P-Value	Significant
* $\tau_{c\,JET}$ vs. $\tau_{c\,Flume}$	Both	0.031	Yes
τ_{cJET} vs. $\tau_{c\,Flume}$	Fescue	0.340	No
$\tau_{c\,JET}$ vs. $\tau_{c\,Flume}$	Bermuda	0.066	Yes
$k_{d\,JET}$ vs. $k_{d\,Flume}$	Both	0.156	No
$k_{d\,JET}$ vs. $k_{d\,Flume}$	Fescue	0.444	No
$k_{d\,JET}$ vs. $k_{d\,Flume}$	Bermuda	0.204	No

* significantly different at P-value < 0.05.

In a flume test, the shear was applied horizontally across the entire surface of the soil sample whereas during a JET the applied stress was vertical at one scour hole location. Also, while running a JET, it was more likely for the impinged water to hit a distinctively large root or conglomeration of roots exposed in the scour hole, limiting erosion during the test and skewing results. Increasing the number of tests could help reduce the skew from those tests.

Field Experiments: Bare versus Root-Permeated Soils

A total of ten side-by-side (20 total) JETs were performed on the restored meander bench at Cow Creek: ten on root-permeated soil and ten on bare soil. Of the root-permeated trials, six were on little bluestem root networks, three were on Bermuda grass, and one was on switch grass. Legacy roots from surrounding vegetation were observed during analysis in all of the bare soil samples taken from around the scour hole, primarily in the lower root samples. Additionally, pieces of erosion matting placed during the meander restoration were discovered in several of the lower root cores and influenced scour depths when the JET scoured greater than 40 mm. Both of these factors may have had an effect on the equilibrium scour depth of JETs. With that said, a significant correlation was observed between the scour hole volume and equilibrium scour depth (Figure 7).

The k_d values of both bare and root-permeated soil samples ranged over one order of magnitude (3.1 to 23.7 cm^3/N-s, Figure 8), and τ_c values ranged over two orders of magnitude (0.01 to 1.60 Pa, Figure 8). As predicted by the hypothesis, most JETs on root-permeated soils exhibited a lower erosion rate relative to the applied τ as compared to the bare soil. The τ_c value was typically higher for the root-permeated tests (Figure 8), suggesting the greater surface area of the upper roots may relate to the overall higher range of τ_c values. The k_d values did not vary significantly between the root-permeated and bare soil JETs, which does not support the hypothesis that greater root surface area would correlate with a lower k_d (Figure 8). Again,

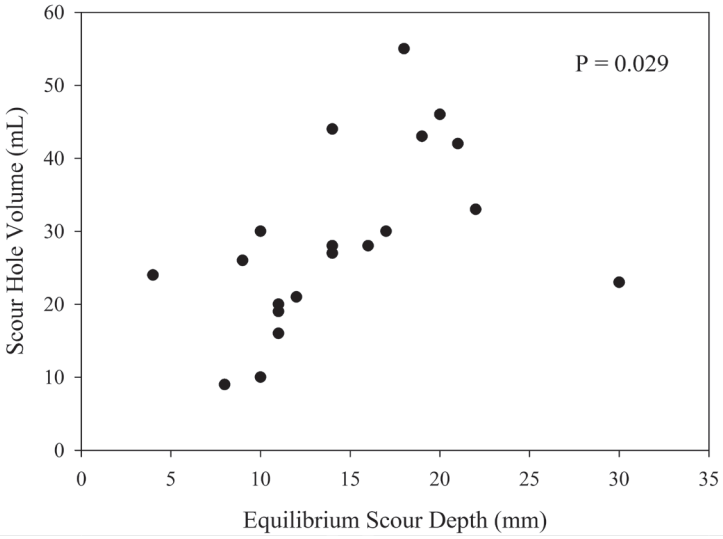

Figure 7. Relationship between equilibrium scour depth and approximated scour hole volume for all field tests, with correlation coefficient.

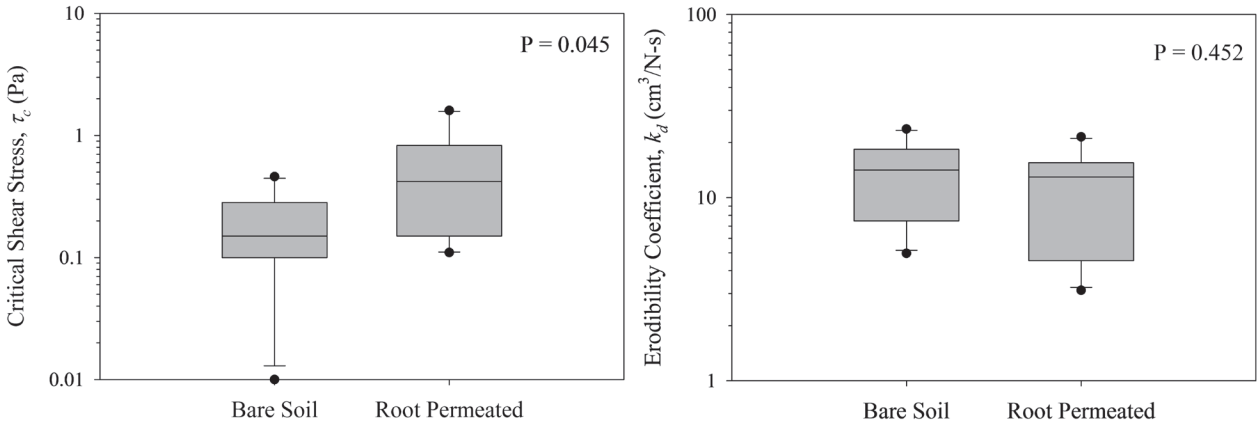

Figure 8. Distribution of critical shear stress, τ_c (Pa) and erodibility coefficient, k_d (cm^3/N-s) between JETs from field tests on bare and root-permeated soil. Shown also is the p-value for a t-test of the difference of means.

such results have implications for considering types of grasses or cover crops for erosion control, specifically when considering the influence of roots on the initiation of detachment. Interestingly, there was as much variability in the flumes and JETs under controlled conditions (Figure 6) as observed in the side-by-side JETs in the field (Figure 8). Typically, much greater variability is reported under field as compared to laboratory or flume conditions.

The Pearson product moment was used to determine correlation coefficients between τ_c, k_d, and the other measured JET, soil, and root variables (Figure 9). There was a statistically significant inverse correlation between τ_c and the equilibrium scour depth and scour hole volume, and a positive correlation with the upper root surface area. The k_d was significantly correlated to the equilibrium scour depth and the scour hole volume, and inversely correlated to the volumetric moisture content.

Sieve and hydrometer tests for soil texture analysis determined all soils were sandy clay loams. Previous research suggested a correlation

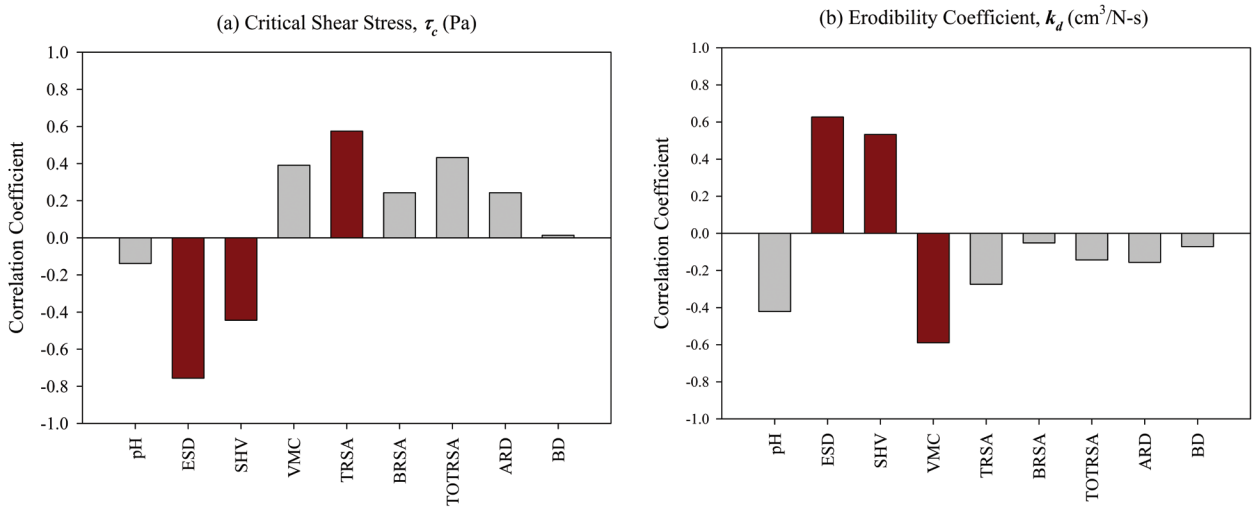

Figure 9. Correlation coefficients for relationships between (a) critical shear stress and (b) erodibility coefficient with other test, soil, and root variables. Significant correlations ($\alpha < 0.05$) are highlighted in red. ESD = equilibrium scour depth, SHV = scour hole volume, VMC = volumetric moisture content, TRSA = upper root surface area, BRSA = lower root surface area, TOTRSA = total root surface area, ARD = average root diameter, BD = soil bulk density.

between the silt-clay content of a soil and τ_c (Julian and Torres 2006), but the data from this research do not show a significant relationship (P = 0.490). The silt-clay content data were used as input into an empirical equation proposed by Julian and Torres (2006) to estimate τ_c for both bare soil and root-permeated soil, and the resulting empirically-estimated τ_c values were more than one order of magnitude higher than the JET-derived τ_c values, supporting the need for process-based determination of erodibility parameters using *in situ* JETs. This research further supports previous findings that erodibility coefficients for cohesive soils are difficult to estimate and empirical relationships should be used with caution.

A significant inverse correlation (P = 0.006) was observed in the data between k_d and the volumetric moisture content (Figure 10). The higher the moisture content, the lower the erodibility of the soil until a threshold at which the soil becomes saturated and erodibility increases. At the same time, increased moisture content helps promote plant growth and hence greater root development over the long term. This is similar to results from a study by Wynn et al. (2008) which showed k_d varied monthly and seasonally due to changes in moisture content. Their results suggest lower soil moisture content was correlated to higher k_d, but it was unclear what direct effect moisture content had on the k_d, if any. Similarly, Ziadat et al. (2010), in a study that measured changes in soil properties along arid hillslopes, observed that increased moisture content and reduced soil erodibility were associated with increased soil clay content. The data from the JETs on the meander bench similarly showed a significant correlation between clay content and volumetric moisture content (P = 0.014). There was also a strong relationship in the data between k_d and the clay content of the soil (P = 0.002).

The presence of "legacy roots" was noted in the bare soil cores. The total exposed root surface area for the bare soil JETs ranged from 5.3 to 80.3 cm^2 and from 25.7 to 284.3 cm^2 for the root-permeated JETs. The average root diameter for the 20 JETs ranged from 0.4 to 0.7 mm. As expected, there was a strong relationship in the data between the total root surface area and average root diameter for the root-permeated soils (P < 0.001). A significant positive correlation was also observed between τ_c and the surface area of the upper roots (TSRA) (Figure 10), although considerable variability was present in the data. This result supports the hypothesis that a greater exposed root surface area will result in a higher τ_c, suggesting that dense, shallow roots allow soils to resist higher detachment forces before the initiation of scour. Lower root surface area was not significantly correlated to τ_c (P = 0.316), which

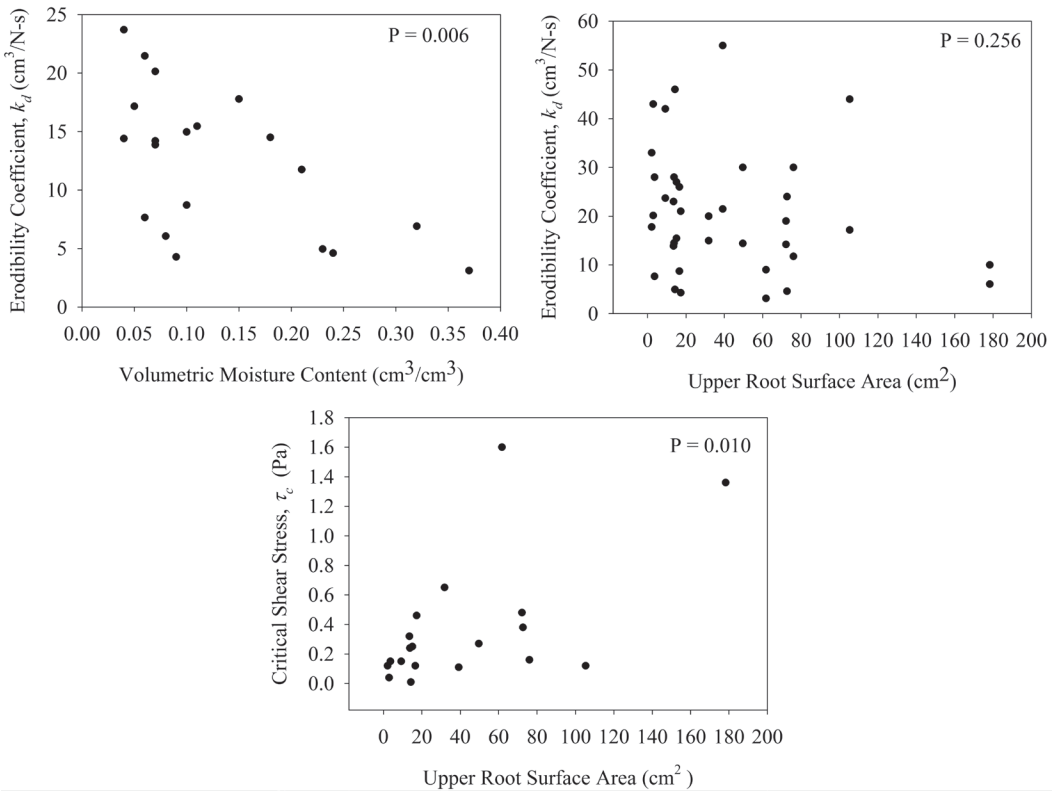

Figure 10. Relationships and associated correlation coefficients between several soil, root, and erodibility parameters from the *in situ* field tests.

was not surprising given that the JET scour depth did not reach to the lower soil depth (Figure 7). There was no significant relationship between the upper root surface area and k_d (Figure 10), which did not support the hypothesis that greater exposed root surface area will be correlated with a lower k_d. This implies that once soil begins to detach, roots have no further influence. The subsequent increase in moisture content in the soil once detachment begins could lead to similar erosion rates after the initiation of detachment.

Summary and Conclusions

This research hypothesized that conventional flume tests on root-permeated soils should result in similar derived erodibility parameters to JETs. The flume tests and the JETs typically provided statistically similar erodibility parameters. The τ_c value was typically lower in Fescue grass compared to Bermuda grass samples, suggesting the greater root surface area of the latter may result in higher τ_c values. We then hypothesized that if *in situ* JETs performed on riparian grass species with shallow root systems have a greater exposed root surface area around the scour hole, then the surrounding soil will have a shallower equilibrium scour depth, a higher τ_c, and a lower k_d. Results from root-permeated soils indicated that near-surface roots had the most significant effect on the erodibility parameters. Upper root surface area was more strongly correlated with these variables than total (combined upper and lower) or lower root surface area. A significant difference was observed in τ_c between root-permeated soil and bare soil. The JETs on root-permeated soils resulted in a higher τ_c range (0.11-1.60 Pa) than bare soil (0.01-0.46 Pa), indicating erosion was initiated at a higher τ_c in root-permeated soils where there was a greater exposed surface area of upper roots. Based on these results, the impact of roots was noticeable in influencing the τ_c. Additional paired bare soil versus root-permeated soil flume tests and JETs would be beneficial on soils with a wider range of average root diameters to expand the analyses beyond the specific conditions of this study.

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