IMPACT OF GRASS ROOT MASS DENSITY ON SOIL DETACHMENT CAPACITY BY CONCENTRATED FLOW ON STEEP SLOPES

G. Zhang, K. Tang, Z. Ren, X.-C. Zhang

ABSTRACT. *The effects of root systems on soil detachment, which are closely related to plant species and flow properties, are not well documented under a wide range of flow hydraulics. The objective of this study was to quantify the effects of root mass density of a versatile switchgrass species (*Panicum virgatum*) on soil detachment capacity, rill erodibility, critical shear stress, and relative soil detachment in a laboratory flume under a wide range of hydraulics using undisturbed soil samples collected from one bare plot (control) and five grass plots with different plant densities. The flow rates varied from 1.32×10^{-3} to 6.58×10^{-3} m^2 s^{-1}, slope gradients from 17.4% to 42.3%, and root mass densities from 0.25 to 17.98 kg m^{-3}. The results showed that soil detachment capacity decreased exponentially with increasing root mass density. The average detachment capacity of soil samples with roots was only one-fourth that of the control, and the rapid decline mostly occurred in the root density range of 0 to 4 kg m^{-3}. Rill erodibility declined exponentially as root mass density increased (R^2 = 0.595, n = 409), whereas no consistent trend for critical shear stress was found. Live roots reduced soil erodibility up to 78% compared with the control. Relative soil detachment decreased as an exponential function with root mass density (R^2 = 0.395, n = 409). However, the exponential decline was less pronounced compared to other studies, probably caused by differences in plant species, amounts of dead root or residue, and experimental conditions.*

Keywords. *Concentrated flow, Detachment rate, Erodibility, Root density, Versatile switchgrass.*

Vegetation communities play a great role in controlling soil erosion in almost every climatic zone (Gyssels et al., 2005). They reduce soil erosion by intercepting rainfall, enhancing infiltration, transpiring soil water, increasing land surface roughness, and adding organic matter to improve soil structure (Muzylo et al., 2009; Glenn and Finley, 2010; Marston, 2010). As vegetation reduces soil erosion significantly, it is often used as one of the most effective measures to control soil and water losses in agricultural catchments (Spaan et al., 2005; Wen et al., 2010), and thus is considered as a significant component in soil erosion models (De Roo et al., 1996; Flanagan et al., 2007).

Many studies have been conducted to assess the effects of canopy, leaf, stem, grass, litter, and residue on soil erosion. Much less attention has been paid to the influences of root systems on water erosion and soil detachment capacity by concentrated water flow (Gryssels and Poesen, 2003; Gyssels et al., 2005; De Baets et al., 2007), especially when roots are uncovered by incising rill flow. The roles of vegetation in controlling soil erosion will be seriously underestimated when only above-ground plant properties are taken into account (De Baets et al., 2007). Thus, to properly account for the effect of plants on soil erosion, it is imperative to quantify the relationships between soil detachment capacity and root density for various plant species under different climate conditions and hydraulic properties and to establish robust relationships or validate existing relationships for estimating the root effects in process-based erosion models.

Some experimental studies have been conducted in the past 20 years to evaluate the potential effects of root systems on soil erosion caused by concentrated flow. Those experiments found that vegetation cover was the most important vegetation parameter for interrill erosion (Gyssels et al., 2005). Soil erosion rate decreased exponentially with increasing root mass in the form of SEP = $e^{-b\mathrm{RP}}$, where SEP is a soil erosion parameter, RP is a root parameter, and b is a constant reflecting the effectiveness of the plant roots in reducing soil erosion rates. For concentrated flow ero-

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sion, the average *b* value was 0.593 when the root mass density (kg m^{-3}) was used as root parameter (Li et al., 1991; Gyssels and Poesen, 2003; Gyssels et al., 2005; De Baets et al., 2006). The role of root systems to control soil erosion mainly depended on the distribution of roots and the number of fibrous roots less than 1 mm in diameter in the top 50 cm of the soil. Plant roots reduce soil erosion because they increase the resistance of the soil, impede water flow, enhance soil permeability, and improve soil physical properties (Li et al., 1992).

The resistance of soil to erosion was closely related to root density and varied greatly with plant species (Mamo and Bubenzer, 2001a, 2001b; Gyssels et al., 2005). The mean soil detachment rate (D_r) for soils with ryegrass roots was reduced by as much as 64% of that for fallow treatment. Rill erodibility (K_r) of rooted soils was also lower than that of fallow soils. Both D_r and K_r decreased exponentially with an increase in root length density (RLD). No significant differences in critical shear stress (τ_c) between fallow and rooted treatments were found. Critical shear stress appeared to be more closely related to surface conditions than to root treatments (Mamo and Bubenzer, 2001a). The mean soil detachment rates of corn and soybean were reduced to one-half that of the fallow soils in a field study (Mamo and Bubenzer, 2001b). There existed exponential relationships between RLD and both D_r and K_r. Rill erodibility depended on the type of plant species and varied greatly between laboratory and field grown crops (Mamo and Bubenzer, 2001b).

The role of vegetation root systems in soil detachment varied with tillage or plant methods. Gyssels et al. (2006) found that the relative soil detachment rates for single-drilled parcels could be reduced by up to 50% compared with a fallow field during the first 75 days of crop growing season, whereas relative soil detachment rates in double-drilled field parcels decreased by up to 60% in the same period. Thereafter, plant roots in double-drilled field parcels reduced relative soil detachment rates by 9% compared with single-drilled field parcels. No significant effect of root density on critical shear stress or channel erodibility was observed due to interactions with other changing parameters (i.e., aging effects).

Root architecture had significant influence on the role of roots in erosion control by concentrated flow (Li et al., 1991; De Baets et al., 2007). Tap roots reduced erosion rates to a lesser extent than fine fibrous roots. Different relationships linking relative soil detachment rate with root density could be established for different root diameter classes. Root density and root diameter explained the variations of observed erosion rates under concentrated flow well for the different soil types.

Spatial and temporal variations in soil properties and root systems increased the difficulty of quantifying the effects of root systems on soil detachment by concentrated flow. Knapen et al. (2008) studied the temporal variability of erosion resistance of loess-derived topsoils under concentrated flow and showed that, apart from soil moisture, soil bulk density, and biologic crust cover, the dry mass of organic material in the topsoil (i.e., roots and crop residue) was another important variable to predict rill erodibility. The detachment rate decreased with root density in grassland and shrubland, whereas no distinct trend was found in the other two land uses (woodland and wasteland) in the Loess Plateau of China (Zhang et al., 2009c). This result was probably caused by the relatively small range of measured root densities, since the study was not specifically designed to investigate the relationship between detachment rate and root density. Further study was needed to investigate the effects of root density on soil detachment in this region.

The available dataset in the literature was not enough to establish an accurate model to simulate the effects of root systems on soil detachment capacity by concentrated flow. De Baets and Poesen (2010) pooled different datasets together to develop empirical models to predict soil detachment rate for both bare and rooted topsoil and to predict erosion reduction potential of plant roots for concentrated flow erosion. The results indicated that root density, soil moisture, bulk density, and shear stress were required to predict the absolute soil detachment rates of bare and rooted soil. The predicted results of erosion reduction depended on the root architecture. For fibrous root systems the predicted results matched the observed data satisfactorily well (R^2 = 0.79), whereas only 10% of the variation in the validation dataset could be explained by a model using root density and mean root diameter as input variables for tap root systems (De Baets and Poesen, 2010). Long-term measurements under different climatic zones, vegetation species, farming systems, and root architectures were needed to accumulate enough data to establish robust relationships or to validate the existing relationships to estimate the effects of root systems on soil detachment in process-based erosion models.

The hydraulic conditions used in these studies varied greatly, making it difficult to compare the results. The experiments of Li et al. (1991, 1992) were carried out in a 1 m long flume, and the hydraulics of flow (e.g., flow velocity, shear stress) could not be determined because the length of flume was too short. The studies of Mamo and Bubenzer (2001a, 2001b) were conducted under carefully controlled conditions; however, the test slope gradients were generally very gentle, varying within the range of 3% to 5%. The length of the flume used in the studies of Gyssels et al. (2005, 2006), De Baets et al. (2006, 2007), and De Baets and Poesen (2010) was only 2 m and was probably too short for flow to reach the steady state, especially on low slopes. Meanwhile, the length of soil samples was 38 cm and was probably too large to avoid the feedback effects of eroded sediment on soil detachment capacity (Cochrane and Flanagan, 1997; Merten et al., 2001; Zhang et al., 2005; Zhang et al., 2009b). Only one constant hydraulic condition was used in the study of Zhang et al. (2009c), and the potential effects of root density on rill erodibility and critical shear stress were not able to be analyzed.

As mentioned above, the effects of root systems on soil detachment depend on plant species, root density, root diameter, root architecture, and soil properties as well as hydraulics of concentrated flow. Most of these factors vary greatly in time and space. More studies are needed to quantify the effects of roots on soil detachment capacity for different plant species under a wide range of hydraulics of overland flow. The objective of this study was to investigate the effects of root mass density of a versatile switchgrass on soil detachment capacity, rill erodibility, critical shear stress, and relative soil detachment rate using undisturbed soil samples in a hydraulic flume under a range of hydraulic conditions.

MATERIALS AND METHODS

The experiments were carried out at the Fangshan field station of Beijing Normal University. The soil contained 16.3% clay, 46.9% silt, and 36.8% sand. The organic matter content was 0.8%. The average bulk density was 1210 kg m^{-3}. Six plots or treatments (5 m length and 4 m width) were established outside, near the laboratory. The versatile switchgrass (*Panicum virgatum*), which was the most popular artificial grass for soil conservation in the Loess Plateau, was planted on 4 July 2010. The seeds were planted at 300, 550, 850, 1150, and 1500 m^{-2} for five plots to obtain different root densities, and another plot was a bare soil control. The seeds were broadcasted uniformly and covered with approximately 2 cm of topsoil. All plots received natural rain and irrigation as needed. The amount of rainfall during the three months of grass growth was 235 mm. Approximately 54 mm of tap water irrigation was applied to each plot to ensure that the grass grew in good condition. The weeds were removed carefully by hand, especially in the control plot.

After three months growth (fig. 1a), the disturbance caused by plant to soil was small. Soil samples were collected on 10 October 2010 to measure soil detachment capacity. A detailed description of soil sample collection and preparation can be found in Zhang et al. (2003, 2009b). Before sampling, the above-ground biomass was clipped at the soil surface so that only the effects of roots on soil detachment rates could be investigated. The soil samples were taken from the surface soil layer with steel rings with a diameter of 9.8 cm and a depth of 5.0 cm. During collection, the steel ring was pressed down slowly into the ground, while the soil and roots surrounding the ring were cut with a knife to make sure the surrounding soil was loose and no roots were caught on the bottom edges of the ring. Following excavation, the sample was turned over, the bottom surface was trimmed with a knife to flush with the ring bottom, and a bottom lid was then replaced. In order to achieve the same water content, the collected samples were moved to the laboratory and wetted for 8 h in a metal container (the water level was increased gradually, and the maximum water level was 1 cm below the soil surface). The samples were then drained for 12 h and weighed. The soil moisture was determined by oven-drying five similarly wetted and drained soil samples and used to compute the initial dry soil mass.

As the flume used in this study has been described in previous publications (Zhang et al., 2008; Zhang et al., 2009a), only its main features are outlined here. The flume was 5.0 m long and 0.4 m wide with a smooth plexiglass bed and glass walls. The upper end of the flume was elevated by a stepping motor, allowing the slope of the flume to be adjusted from 0% to 60% (fig. 1b). The bed slope of the flume could be maintained to within 0.05%. Flow rate was controlled by a series of valves installed on a flow diversion box and was measured at the lower end of flume with plastic buckets and a volumetric cylinder. Flow rate and slope gradient were adjusted to designed values. When the flow became stable, flow depth was measured with a digital level probe (SX40-A, Chongqing Hydrological Equipment Factory, Chongqing, China) at a section 0.6 m from the lower end of the flume. The accuracy of the digital level probe was 0.04 mm. For each combination of flow rate and slope gradient, 12 longitudinal depths were measured. The maximum and minimum flow depths were eliminated from the dataset to reduce the random error in measurement. The average of the remaining ten depths was considered as the mean flow depth, which was used to calculate flow shear stress, as follows:

$$\tau = \rho g H S \quad (1)$$

where τ is the shear stress (Pa), ρ is the water mass density (kg m^{-3}), g is the gravity constant (m s^{-2}), H is the measured mean flow depth (m), and S is the bed slope (m m^{-1}). During the experiment, five flow rates (1.32×10^{-3}, 2.63×10^{-3}, 3.95×10^{-3}, 5.26×10^{-3}, and 6.58×10^{-3} m^2 s^{-1}) and four slope gradients (17.4%, 25.9%, 34.2%, and 42.3%) were used.

Just prior to the start of the experiment, the drained soil sample was placed in a 10 cm hole in the flume bed,

Figure 1. (a) Growing grass and (b) experimental setup.

located at a distance of 0.5 m above the lower end of flume, with the sample surface at the same level as the flume bed. Soil detachment rate (D_c, kg m^{-2} s^{-1}) was calculated using the following equation:

$$D_c = \frac{M_o - M_f}{At} \tag{2}$$

where M_o is the initial dry mass of soil sample (kg, the wet weight of the soil sample minus the water weight within the soil sample), M_f is the final oven-dry mass of the soil sample (kg), A is the section area of the soil sample (m^2), and t is the time period of the test (s). One sieve (1 mm) was installed below the flume outlet to collect potentially lost roots during the test. After the test, the remaining wet soil sample was oven-dried at 105°C for 12 h and weighed to determine the final dry mass (M_f) in equation 2. The roots within the soil sample were then collected by washing over a sieve (1 mm) and oven-dried for 12 h at 65°C (including the roots collected during the test). The dry roots were weighed and used to calculate root mass density (RD, kg m^{-3}).

For each combination of flow rate and slope gradient, four soil samples from each root treatment were tested. For the control (bare plot), the four measured detachment rates were averaged and the mean value was used as the detachment capacity for that combination of flow discharge and slope gradient. The measured detachment capacity of each rooted sample was analyzed individually because the root density was different. Altogether, 469 soil samples (80 from the control plot, and 389 from the grass plots) were tested, since some were destroyed during the experiments.

To evaluate the effects of root density on erodibility and critical shear stress, the measured detachment capacities were divided into 14 groups according to root density and plotted with flow shear stress. The slope of fitted linear line was rill erodibility, and the intercept on the x-axis was critical shear stress for that mean root density (Flanagan et al., 2007). The relative soil detachment (RSD, dimensionless) was computed as a ratio of soil detachment capacity for the rooted soil samples to that for the control soil sample, tested under the same hydraulic condition. The relationship between RSD and RD was further analyzed. Nonlinear regression and simple regression were used to analyze the effects of root density on soil detachment rate, soil erodibility, critical shear stress, and relative soil detachment. The regression results were evaluated by the coefficient of determination.

Results and Discussion

The measured root mass density of soil samples ranged from 0.25 to 17.98 kg m^{-3} with a mean value of 3.96 kg m^{-3}. The measured root mass varied from 0.07 to 1.79 g with a mean of 0.47 g. The measured root diameter ranged from 0.10 to 0.96 mm with a mean value of 0.49 mm, and the manually measured root length ranged from 0.30 to 6.09 m with a mean value of 1.99 m (table 1). The measured soil detachment rates related to flow discharge, slope gradient, and root density. The range of the y-axis values in figure 2 increased with slope gradient from 0.40 to 1.20 kg m^{-2} s^{-1}. Comparing the graphs of different slope gradients, it was clear that soil detachment rates of both the control and rooted soil samples increased with increasing slope gradient.

The measured average detachment rates decreased as root density increased on all four slopes tested in this study. The mean detachment rate of rooted soil samples decreased from 0.299 kg m^{-2} s^{-1} for the control to 0.074 kg m^{-2} s^{-1} for the pooled samples of all root treatments (table 2). In other words, the mean detachment rate of rooted soil samples was only one-fourth that of the control.

This result corroborates recent experiments on rooted soils, which indicated that soil detachment rates decreased as root density increased (Mamo and Bubenzer, 2001a, 2001b; Gyssels and Poesen, 2003; De Baets et al., 2006; De Baets and Poesen, 2010). Similar to the results of De Baets et al. (2006), the decline in detachment rate mostly occurred in the root density range of 0 to 4 kg m^{-3}. As shown in table 2, the mean detachment rate of the rooted soil samples was only one-third that of the control when root density was less than 4 kg m^{-3}. When root density varied from 4 to 10 kg m^{-3}, the detachment rate declined continuously but at a low rate. When root density was greater than 10 kg m^{-3}, the detachment rate was almost stable, with a mean value of 0.058 kg m^{-2} s^{-1}. The decrease in detachment rate with root density seemed to be independent of the applied shear stress within the tested range of 4.79 to 23.38 Pa in this study.

For concentrated flow erosion, detachment rate could be defined as (Foster, 1982):

$$D_r = K_r(\tau - \tau_c) \tag{3}$$

where K_r is rill erodibility (s m^{-1}), τ is flow shear stress (Pa), and τ_c is the critical shear stress (Pa). Previous studies showed that root density had great influence on erodibility of concentrated flow erosion (Mamo and Bubenzer, 2001a; De Baets et al., 2006; De Baets and Poesen, 2010). For comparison, the data from this study were divided into 14 groups according to root density (table 3), and the relationship between rill erodibility and root density was analyzed. It clearly showed that K_r decreased with an increase in root density, especially when root density was less than 2.4 kg m^{-3}. Rill erodibility fluctuated around 0.08 s m^{-1} when RD was greater than 2.4 kg m^{-3}. The mean erodibility of rooted soil samples was only 22% that of the control. The best fit between rill erodibility and root density was (fig. 3):

$$K_r = 0.018e^{-0.410RD} \quad (R^2 = 0.520,\ n = 14) \tag{4}$$

The critical shear stress τ_c (the intercept of the regression of equation 3 along the x-axis) varied considerably (table 3 and fig. 4). Apparently, τ_c increased with root density, as shown by the fitted line in figure 4. However, regression analysis showed no significant trend between RD and τ_c in this study, indicating that the critical shear stress fitted with equation 3 may likely be independent of root mass density. More studies are needed to test this speculation. However, this result was in line with the conclusions of Mamo and Bubenzer (2001a), Gyssels et al. (2006), and De Baets and Poesen (2010). Critical shear stress was probably more closely related to surface condition than to root density (Mamo and Bubenzer, 2001a). Assuming a constant critical shear stress, nonlinear regression analyses between detachment rate, flow shear stress, and root density produced the following relationship (fig. 5):

$$D_r = 0.032e^{-0.385RD}(\tau - 6.058) \quad (R^2 = 0.595,\ n = 409) \tag{5}$$

The calculated relative soil detachment (RSD) decreased with increasing in root density (fig. 6), which indicated that soil detachment decreased as root density increased. This result was in accordance with the results reported by De Baets et al. (2007) and De Baets and Poesen (2010). The best fit between root density and relative soil detachment was:

$$\text{RSD} = e^{-0.409\text{RD}} \quad (R^2 = 0.359,\ n = 409) \tag{6}$$

The exponent (-0.409) of equation 6 was significantly less negative than the values of -0.593, -2.50, -1.14, and -0.93 reported by Gyssels et al. (2005, 2006), De Baets et al. (2006), and De Baets and Poesen (2010), respectively. A lower exponent means a faster reduction in soil detachment (fig. 7). For equations of Gyssels et al. (2006), De Baets et al. (2006), and De Baets and Poesen (2010), the RSD reached a constant value, close to zero at a root density of 4 kg m^{-3} (the calculated values were 0.055 for all three equations). When RD was greater than 10 kg m^{-3}, the RSD was almost the same for all four equations.

The differences in the exponents of equation 6 from other studies probably resulted from differences in plant species, amounts of dead roots or residue in soils, and experimental conditions and procedures. Plant species may be the most likely reason causing the differences in the exponents because root architecture, length and mass ratio, and depth distribution often vary substantially between species. In the above-mentioned studies, soil samples were collected from different land uses, such as winter barley, spring wheat, soybean, carrots, oats, mustard, facelia, etc. The root surface area, the number of fine roots, and the root architecture, which were closely related to erosion reduction by root systems (Li et al., 1991, 1992; Gyssels et al., 2005; De Baets et al., 2007; De Baets and Poesen, 2010), were quite different among plants, soil depths, and even plant development stages.

The second explanation was related to amounts of dead roots or residue. The existence of dead root or residue could enhance soil resistance to erosion and increase the ability of root systems to reduce soil erosion (Gyssels et al., 2005; De Baets and Poesen, 2010). In this study, the soil was sieved, and the grass was grown for only three months. No dead roots or residue existed within the soil samples, and a greater RSD might be expected. Lastly, differences in soil properties, such as bulk density and clay content, and hydraulic conditions including slope, discharge, and test area roughness might have resulted in different responses of RSD to root mass density due to nonlinear interactions among these factors. Generally, the benefits of soil and water conservation measures decreased with slope gradient, and even failed at steep slopes. However, the statistical results showed that no identical trend was found in changes of relative soil detachment as slope gradient increased from 17.4% to 42.3% in this study (table 4).

Table 1. Statistical characteristics of measured root parameters.

Parameter	Min.	Max.	Mean	SD	*N*
Root mass (g)	0.07	1.79	0.47	0.42	47
Root diameter (mm)	0.10	0.96	0.49	0.14	807
Root length (m)	0.30	6.09	1.99	1.42	47

Table 2. Statistical parameters of soil detachment capacity (D_c, kg m^{-2} s^{-1}) of soil samples with different root densities.

Soil Sample	Min. D_c	Max. D_c	Mean D_c	SD	*N*
Rootless	0.011	1.137	0.299	0.286	20
Rooted					
RD = 0-4 kg m^{-3}	0.000	0.637	0.089	0.086	232
RD = 4-18 kg m^{-3}	0.000	0.242	0.051	0.048	157
Pooled data	0.000	0.637	0.074	0.075	389

Table 3. Rill erodibility and critical shear stress of soil samples with different root densities.[a]

RD (kg m^{-3})			K_r	τ_c		
Mean	Min.	Max.	(s m^{-1})	(Pa)	R^2	*N*
0	0	0	0.044	6.451	0.653	20
0.767	0.250	0.999	0.020	6.116	0.474	29
1.393	1.249	1.499	0.009	3.408	0.465	33
1.895	1.748	1.998	0.016	6.827	0.620	34
2.399	2.248	2.498	0.009	4.266	0.700	28
2.855	2.747	2.997	0.010	5.109	0.608	44
3.391	3.247	3.497	0.007	5.881	0.620	33
3.835	3.746	3.996	0.009	6.641	0.684	31
4.340	4.246	4.496	0.008	6.593	0.680	24
4.879	4.745	4.995	0.010	6.923	0.684	28
5.550	5.245	5.994	0.009	7.349	0.632	36
6.605	6.244	6.993	0.007	7.239	0.743	27
7.536	7.243	7.993	0.005	4.600	0.454	23
10.109	8.242	17.982	0.007	8.268	0.638	19

[a] RD = root density, K_r = rill erodibility, and τ_c = critical shear stress.

Table 4. Statistical parameters of relative soil detachment (RSD) of soil samples on different slope gradients.

Slope (%)	Min. RSD	Max. RSD	Mean RSD	SD	*N*
17.4	0.000	0.942	0.239	0.207	95
25.9	0.001	0.986	0.302	0.226	98
34.2	0.045	0.931	0.317	0.228	96
42.3	0.025	0.977	0.281	0.192	100

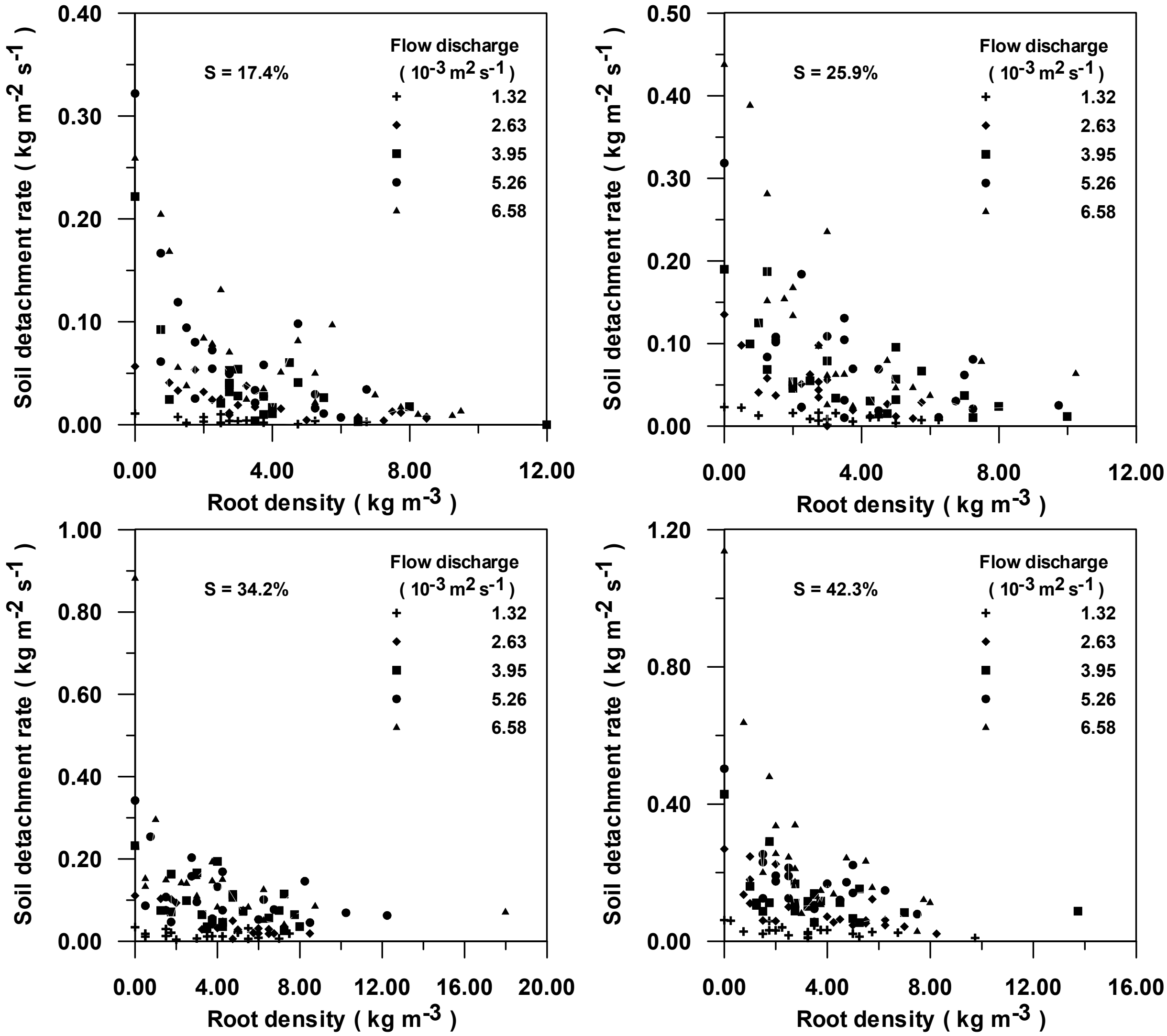

Figure 2. Soil detachment rate as a function of root density for each slope with different discharge rates.

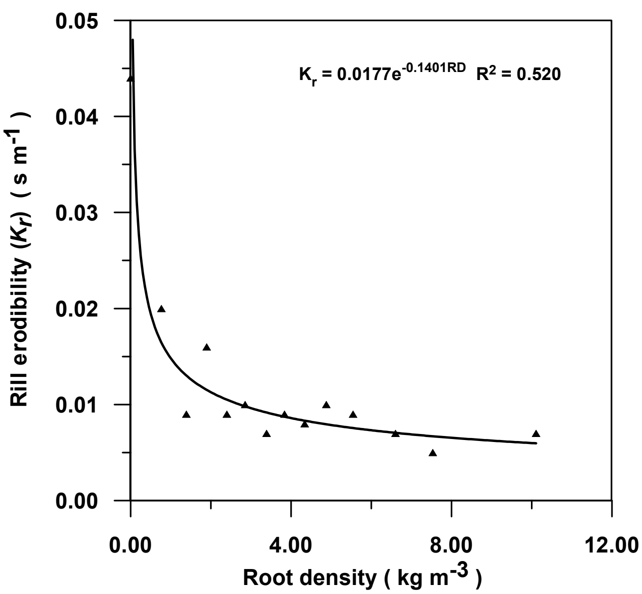

Figure 3. Rill erodibility (K_r) as a function of root density.

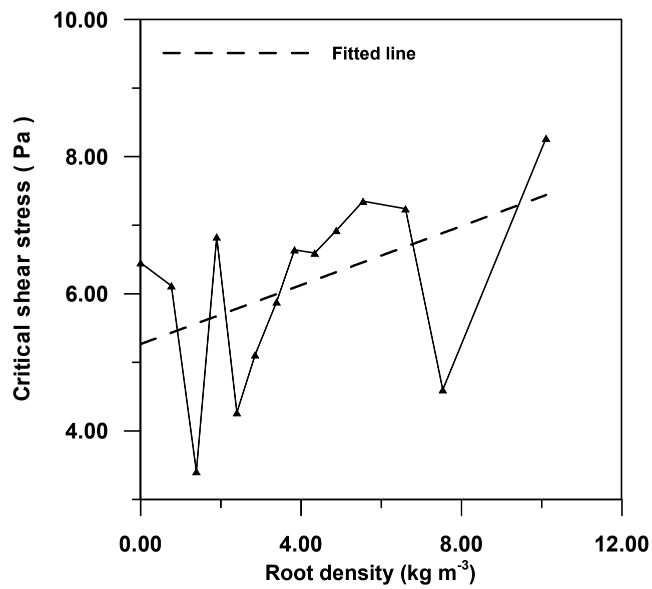

Figure 4. Critical shear stress as a function of root density.

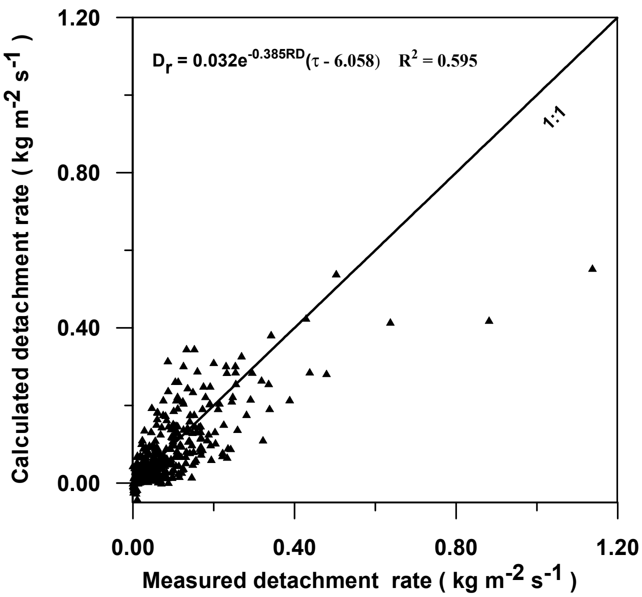

Figure 5. Calculated detachment rate (using eq. 5) vs. measured detachment rate.

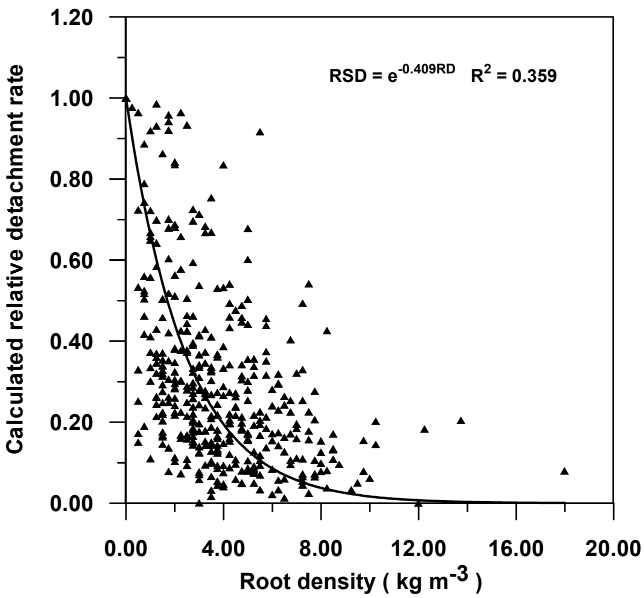

Figure 6. Calculated relative detachment rate as a function of root density.

CONCLUSION

The effects of root density of a versatile switchgrass on soil detachment capacity, rill erodibility, critical shear stress, and relative soil detachment were evaluated using undisturbed soil samples under a wide range of hydraulic conditions. The results showed that soil detachment rate decreased exponentially with increasing root density. The average detachment rate of rooted soil samples was only one-fourth that of the control, and the rapid decline mostly occurred in the root density range of 0 to 4 kg m^{-3}. Rill erodibility declined exponentially as root density increased, whereas critical shear stress was independent of root density. Rill erodibility of rooted grass soil could be reduced up to 78% compared with bare soil of the control.

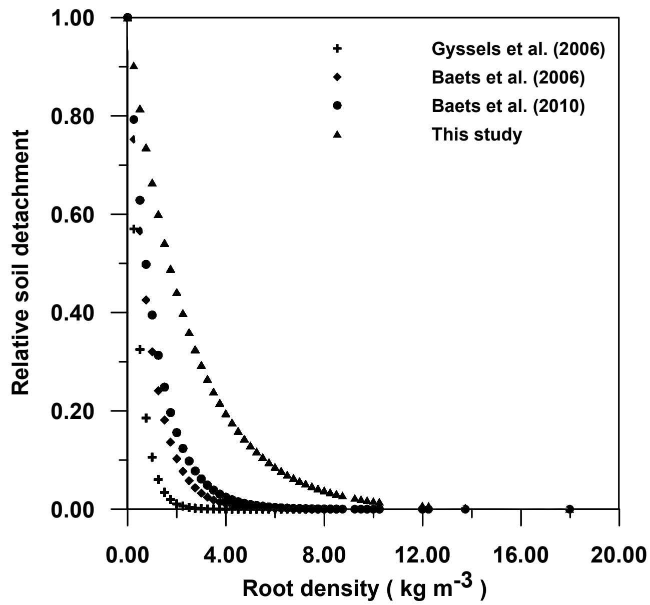

Figure 7. Relative detachment rate calculated using equations reported by others and the regression equation of this study.

Relative soil detachment decreased as an exponential function with root density. However, the regression exponent of -0.409 was substantially greater than those reported by others, probably due to influences of plant species, dead roots or residue, and experimental setup. Further studies are needed to evaluate the potential effects of root systems of different plant species on soil detachment rate and to upscale the effects of a single species to ecosystem landscape level.

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