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Research Paper

Effects of plant root density on the erodibility of lateritic topsoil by simulated flume experiment

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Abstract: A laboratory facility was built to quantify effects of grass roots on the erodibility of lateritic topsoil by concentrated flow erosion. The design allowed slope gradient and flow rate to be controlled. The hydraulic flume was used to test the concentrated flow erosion from three lateritic topsoils (bare, scatter grass-root-permeated and densely grass-root-permeated) and exposed to two slopes (25 and 35%). The aim of the test was to formulate a model to represent effect of grass roots density on topsoil erosion by concentrated flow for lateritic topsoil of Paschim Medinipur, West Bengal, India. The detachment rates of undisturbed topsoil samples collected from twenty (three bare soil, eight scatter grass and nine densely grasses) soil monitored through a 1.82 m long, 0.094 m wide hydraulic flume under two different slope condition (25 and 35%). Velocity of flow was set at 0.000492 and 0.00064 m3s-1 and flow shear stresses (τ,) ranged between 3.8 and 17.5 Pa. The results indicated that a significant negative exponential relationship between relative soil detachment (RSD) and roots density (RD) was detected. This study yielded one prediction equation that allowed comparison of their efficiency in assessing soil detachment rate in concentrated flow. The equation including the root density (RD) shows a better correlation coefficient (R2 = 0.73067). It may be concluded that the formula based on root density (RD) has the potential to improve methodology for assessing soil detachment rate in concentrated flow for lateritic topsoils.

Keywords: Absolute soil detachment; relative soil detachment; root density; concentrated flow

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Introduction

Gully erosion is one of the forms accelerating soil erosion. Its occurrence often indicates an extreme form of land degradation warranting special attention (Daba et al., 2003). Soil loss rates by gully erosion may represent more than half of the total sediment yield caused by water erosion (Tang and Zhang, 1998; Valentin et al., 2005). Recent studies indicate that rill-gully erosion represents an important sediment source in many environments (Poesen et al., 2003, 2009). Land degradation through rill-gully erosion is of great concern in the lateritic badland topography of western part of West Bengal; because every year about 1.04 lakh ha area is affected by rill-gullies (Sharda et al., 2007). Rills and gullies are developed due to concentrated flow erosion, resulting from the detachment and displacement of soil particles (Govers et al., 1990).

Prevention and control measures for rill-gully erosion are often practiced by increase in soil cover. The surface cover by geotextiles, rock fragments, mulches and vegetation is effective in the reducing runoff and soil erosion rate (Poesen et al., 2004; Gyssels et al., 2005; Smets et al., 2008). The plant's canopy reduces soil erosion rates by intercepting raindrops, enhancing infiltration, transpiring soil water (Styczen and Morgan, 1995). Numerous studies have been conducted to evaluate the effect of vegetative cover on soil erosion. The results indicated that soil erosion decreased with increasing vegetation cover (Li, 1993; Zhang et al., 2003; Wei et al., 2006; Zheng, 2006; Zhou et al., 2006).

The below-ground biomass i.e. root systems act to form anchors that stabilize loose soil (Gyssels and Poesen, 2003). Roots play an essential role in soil properties such as aggregate stability, infiltration capacity, soil bulk density, soil texture, organic and chemical content and shear strength (Miller and Jastrow 1990; Reubens et al. 2007). In recent years, many studies have been conducted, investigating the effects of plant roots on soil aggregate stability (Monroe and Kladivko, 1987), soil shear strength (Waldron, 1977), soil penetrability (Wu et al., 2000), soil erodibility (Mamo and Bubenzer, 2001b), and soil anti-scouribility (Li and Xu, 1992; Wu et al., 2000; Zhou and Shangguan, 2005), all of which affect or represent soil erodibility. According to Li and Xu (1992) and Wu et al (2000), the density of fine roots, defined as the number of roots < 1 mm in diameter per unit soil volume, has a considerable effect on soil anti-scouribility. Mamo and Bubenzer (2001a, 2001b) reported that soil erodibility decreased sharply with increasing root length density (cm of root length per cm3 of soil). Gyssel et al., 2005 established an experimental relation between root density and relative soil loss by concentrated flow. In the present study area, rill and gullies are developed intensively through concentrated flow of rain water and requires proper understanding of mechanism of erosion and effective of plant to resist erosion in order to proper for sufficiently reliable management techniques. Whether the same experimental relation exists between plant root and soil erodibility is the question of enquiry. The objective of this study is to explore the importance of plant root characteristics on concentrated flow erosion resistance and to quantify the relationship between relative soil detachments rate (RSD) and roots density (RD) of sandy loam topsoils in the unique situation of the western part of West Bengal.

Martial mad Methods

Study area

Twenty topsoil samples was collected by the monolith method of Bohm (1979) from the lateritic environment with three different vegetative cover situations i.e. Bare soil (three), Scatter grass roots (eight) and Densely grass roots (nine) in the rill -gully affected areas (22°24.697' N, 87°17.798' E to 22°24.798' N, 87°17. 895' E) and located about 1 km southwest of the town of Medinipur in West Bengal, India, near Vidyasagar University. The climate is semi-arid, with a high inter-annual variability of rainfall. Mean annual rainfall is about 1850mm and potential evaporation reaches to 1692.3 mm. Most of the rain is concentrated in summer monsoon. Mean annual temperature is near about 28.4° C, and the average summer (May) and winter (December) temperatures are 40.9° C and 7.5 ° C respectively. During prolonged dry season (October to May) most of the vegetative cover becomes dry and intensive pasturing removes surface cover to a great extent. Only below ground biomass remains present throughout the season and that plays important role in resisting erosion.

Table 1. Soil texture (%) and bulk density of twenty one topsoil samples

Soil	Sand (0.06-0.002) mm	Silt loam and Clay (<0.06 mm)	Bulk density (g/cm3)
Micro-aggraded Sandy loam soil	67.12	32.88	0.82-1.43

Soil sample collection and preparation

Undisturbed twenty one topsoil samples were collected from three different places; a set consisted of three bare soil samples, eight grass samples with low sowing density and nine grass samples with high sowing density for the experiments. The grass that was used is a mixture of the following species: 23% of Andropogon aciculate (Poaceae), 40% of Eragrostis cynosuroides (Poaceae), 17% of Panicum maxima (Poaceae), and 20% of Saccharum munja (Poaceae). For sampling, the metal boxes (0.35 m long, 0.09 m wide and 0.08 m deep) were driven into the soil using a hammer. To protect the top of the metal box, a wooden plank was placed on the top during the hampering. After sampling, the above ground biomass (i.e. stem) was clipped up to the level of soil surface and the samples were placed in a container with a constant water level 3.5 cm below the soil surface to allow for slow capillary rise for 8 hours, in order to obtain similar soil moisture contents for all samples. In this process, all samples were stored in a normal room temperature (20-25ºC).Twelve hours before the experiments, the soil samples were taken out of water to drain.

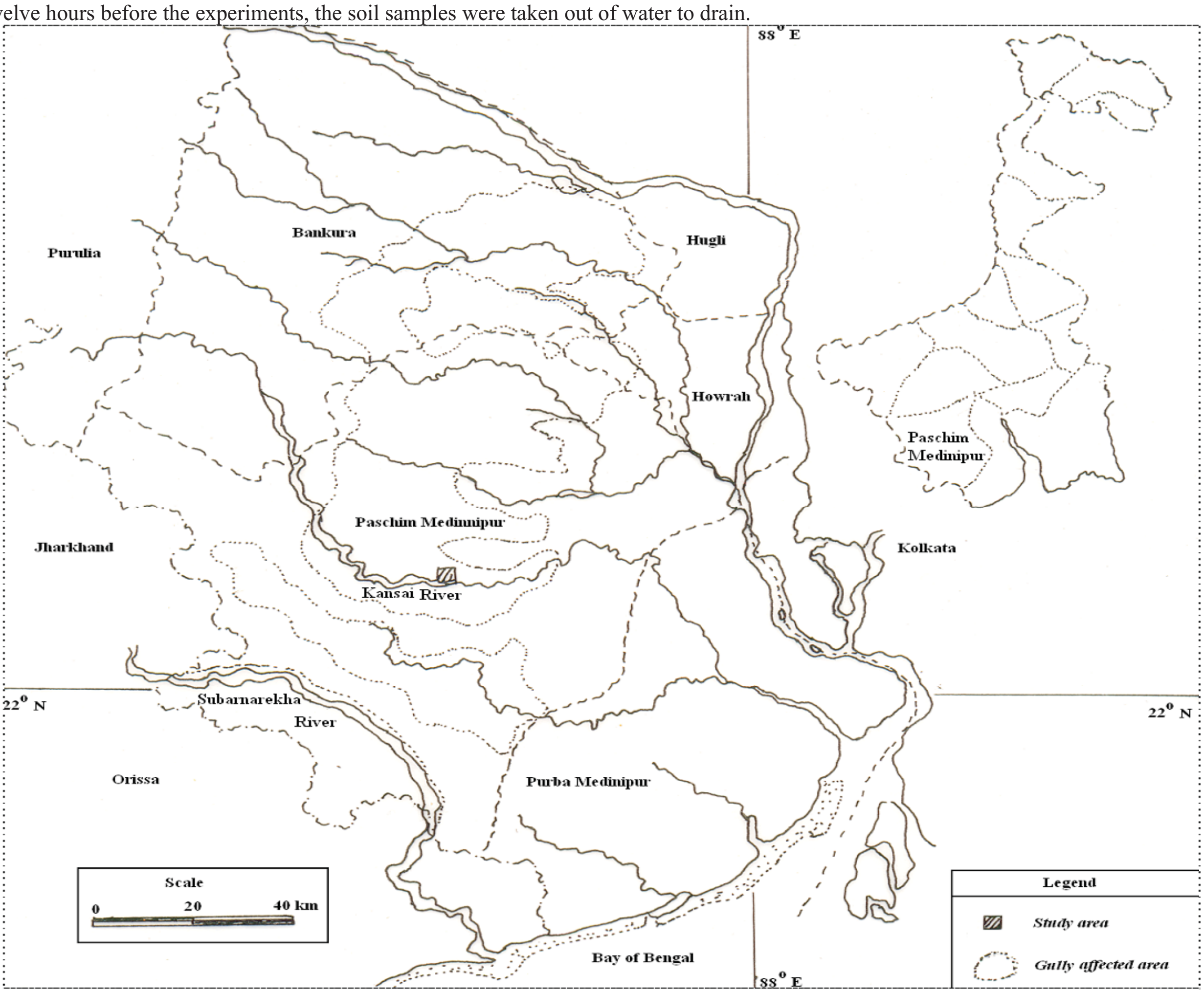

Figure 1. Location of the study area

Figure 2. Hydraulic flume used to measure detachment rates from root permeated topsoil samples.

Experimental design

Laboratory experiments on simulated concentrated flow were conducted with a flume similar to the description by Kanpen et al., 2007a (Figure 2; length= 1.82 m, width= 0.094 m). The flume contained an opening at its base, equaling the size of the metal sample box (length =35 cm, depth = 9 cm, width = 8 cm), so that the soil surface of the sample was at the same level of the flume surface. When inserted in the flume, the surface of the soil sample in the steel box forms a continuum with the bed of the flume. To reduce edge effects, water losses are prevented at the contact between the soil sample box and the flume by sealing with painter's mastic. Soil surface slope (S), flow discharge (Q), mean bottom flow velocity, water temperature and sediment concentration were measured. Two slope gradients were set between 25, and 35%. Flow discharge (Q) was measured 25 times before and after the experiment by collecting the volume of water during 15 second time. Simulated flow discharge ranged between 0.000492 and 0.00064m3 s-1. Values of total flow shear stress (τ , Pa) were calculated using the equation (1) and that ranged between 3.8 and 17.5 Pa (Nachtergaele and Poesen, 2002; Wang et al., 2011)

$$\tau = \rho_w gRS \quad \text{……………..} (1)$$

Where, τ is mean bottom flow shear stress (Pa), ρ_w is water density (kg m-3) with temperature being taken into account, g is acceleration due to gravity (m s-2), S is sin $(\alpha°)$, in which α is slope angle of soil surface (%), and R is hydraulic radius (m):

$$R = \frac{w.d}{w+2d} \quad \text{………………} (2)$$

Where, w is flume width (i.e. 0.094 m), d is depth of the water flow in experimental flume (m):

$$d = \frac{q}{u} \quad \text{………………………}(3)$$

Where q is unit flow discharge (m2 s-1) and u is average flow velocity (m s-1). Flow velocities are measured during the experiment by recording the travel time (n=20) of a dye tracer technique (potassium permanganate solution) over a distance of 1.82 m. Water depths ranged between 0.003 and 0.004m. For sediment concentration measurement, runoff water and detached sediment are collected 10 times during the experiment run (each experimental run lasts 1.50 minute) in 200 buckets at outlet of the flume. The mean soil detachment rate (kg s-1 m-2) was calculated by multiplying the mean gravimetric sediment concentration of the 10 buckets (kg l-1) with average runoff discharge (l s-1) divided by soil sample surface area (m2).

Measurements after experiment

Soil erosion

The collected sediment was separated from the water by settling during at least 12 hours and then decanted the water. The sediments were oven dried at 105º C and dry sediment was weighted.

The absolute soil detachment rate ((ASD; kg m-2 s-1) was calculated using the equation:

$$ASD = (SC * Q) / A \quad \text{…………………………………………}(4)$$

SC= sediment concentration (kg l-1), Q is flow discharge (l s-1) and A is area of soil sample surface (m2).

ASD values were calculated for each runoff sample taken every 15 second during 150 second. Since ASD varies over time, the mean and Standard deviation ASD was calculated for each sample and used as an indicator of soil erosion susceptibility during concentrated flow (Table 2 and 3).

Root parameters

After each experiment, roots were separated from the soil by wet hand washing method (Schuurman and Goedewaagen, 1965) and the root samples were washed and sieved using a 0.5mm sieve, by sprinkling water at low water pressure (De Baets et al. 2006). Then the root density properties of each sample were measured manually flowing:

Root density (RD)

$$RD = \frac{M_D}{V} \quad \text{……………………..……………..………………} (5)$$

Where MD is dry living root mass (g) and V is volume of the sample box (cm3)

Analysis methods

All analyses were performed using MS Excel and Origin-8 program. Significant differences among treatments for relative soil detachment rate and plant root density were determined using the LSD (least significant difference) procedure for a multiple range test at the 0.05 significance level. The relationships between relative soil detachment rate (RSD) and root density (RD) were analyzed by a non-linear regression method. The regression results were evaluated by the coefficient of determination.

Results

Absolute soil detachment rate (ASD)

In the present study at 25 degree slope angle, mean absolute soil detachment rate (kg m-2 s-1) for bare soil, scatter grass roots and densely grass roots were 0.005915; 0.00527125 and 0.003627083 respectively (table-2). With 35 degree slope angle, mean absolute soil detachment rate (kg m-2 s-1) those were 0.016963333; 0.008227917 and 0.004047083 respectively (table-3). It is clear that the soil erosion is decrease with increase grass roots density. This variation in ASD of the bare topsoil justifies the use of RSD to compare the effects of different root densities on the soil detachment rates. Figure 3 a, b shows the comparative temporal change in ASD during the experiment with scatter grass roots and densely grass roots and bare topsoils. Mean ASD decreased exponentially with time due to soil consolidation and soil stability caused by effective stresses in soils (Nearing et al 2005). Cruse and Larson (1977) showed that these stresses increase the soil resistance to splash detachment by raindrops. According to Nearing et al., (2000) soil erodibility also decreases due to increased soil shear strength that resulted from stresses induced by drying.

Relation between root density (RD) and relative soil detachment rate (RSD)

RSD values were calculated in table 2 and 3. A non-linear regression analysis showed the decreasing trend of RSD (r2=0.73067) with increasing RD (Figure 4). This was probably due to living plant roots that improved soil physical properties and increased aggregate stability and infiltration (Wu et al., 2000; Mamo and Bubenzer, 2001a, 2001b), resulting in reductions of runoff and sediment yields. The increase in aggregate stability and infiltration, according to Monroe and Kladivko (1987), could be attributed in part to the physical reinforcement of aggregates and adhesion of soil particles by roots, which were closely related to the root area in contact with soil particles. Thus, RD was an important indicator of these behaviors. The greater the mean value of RD, the larger the area of soil in contact with the roots. Concentrated flow erosion can be reduced by the presence of roots in the topsoil (Knapen et al., 2007b). The relation between RSD and RD was established using the data available from experiment and is expressed in equation 6. A significant negative exponential relationship between relative soil detachment rate (RSD) and root density (RD) was obtained at the 10% level (R2 = 0.73067, P = 0.05) (Figure 4). A new equation for relative soil detachment rate (RSD) in concentrated flow was obtained:

$$RSD = 0.79038e^{-1.3537RD} + 0.06458$$

$$(R^2 = 0.73067,\ P<0.05) \qquad \ldots\ldots (6)$$

The results of the current study indicate that soil detachment rate was closely related to root density. Equation (6) was convenient and effective for predicting soil detachment rate in lateritic topsoil from in the area under study. Soil detachment rates also had great temporal variation caused by temporal variability of soil properties as well as root traits (Knapen et al., 2007a; and Zhang et al., 2008).

Conclusion

It is necessary to understand the effectiveness of plant roots in resisting concentrated flow erosion before proposing plant species for soil conservation. Present laboratory experiments established a significant exponential relation between relative soil detachment and plant root density by concentrated runoff in undisturbed lateritic topsoils.

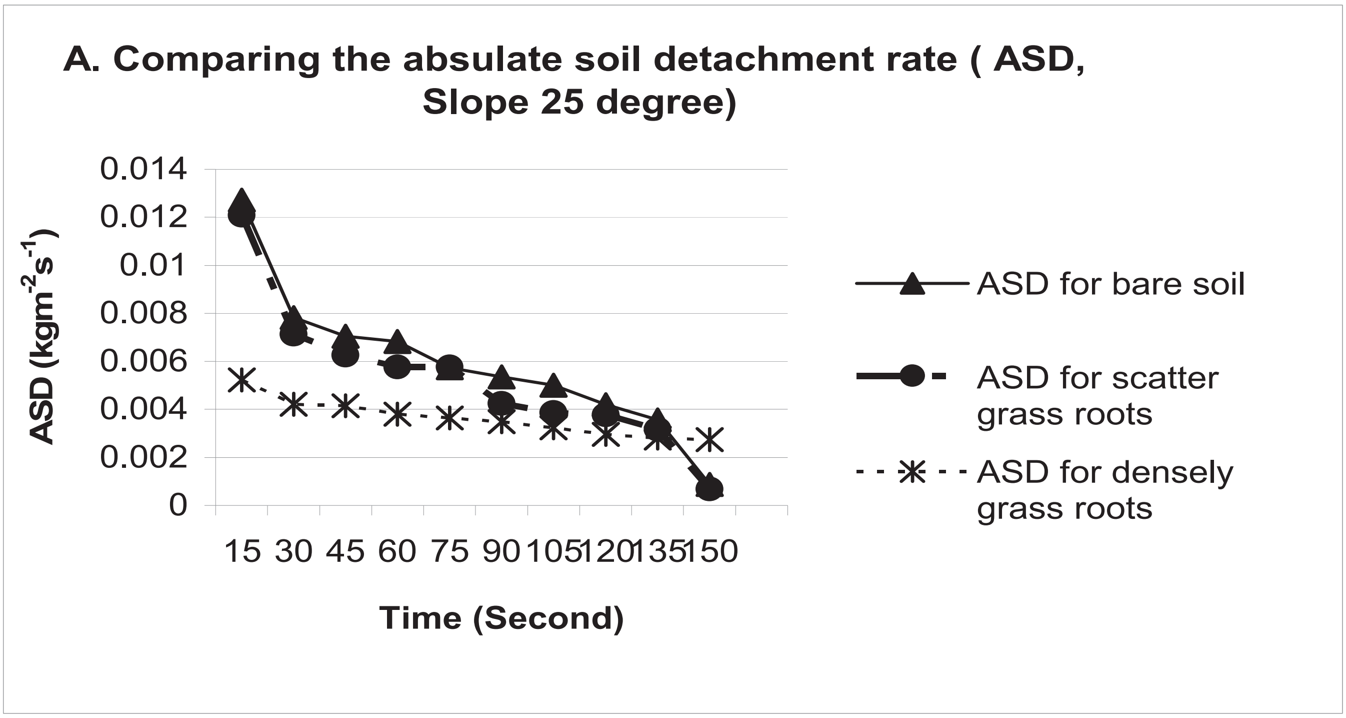

Figure 3 (a). Variation in absolute soil detachment rate (ASD, kg m^{-2} s^{-1}) during three experiments with 25 degree slope angle

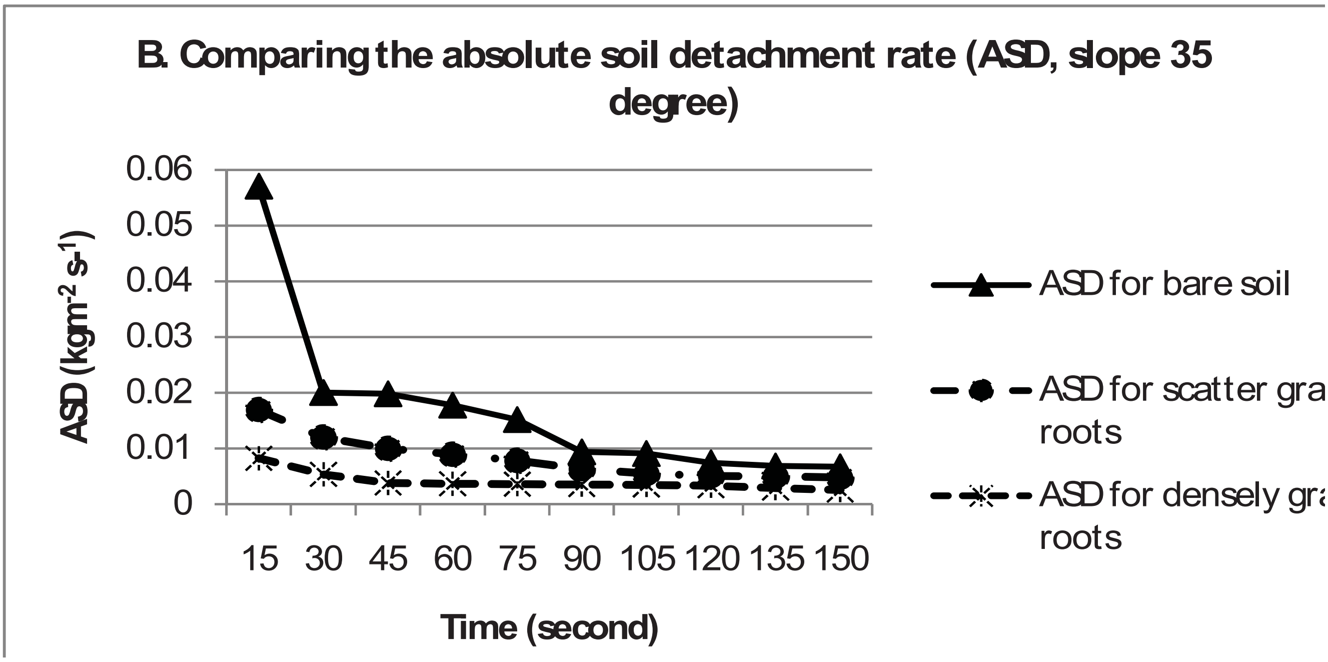

Figure 3 (b). Variation in absolute soil detachment rate (ASD, kg m^{-2} s^{-1}) during three experiments with 35 degree slope angle.

The statistical model of Equation (6) developed in the current study is helpful to have an understanding of the processes operating for soil detachment and effectiveness of plant root to increase soil stability against concentrated flow. The experiment was run in saturation condition. These are seasonal variability of moisture and other soil properties. This model has a scope for further improvement by incorporation other factors, considering their seasonal variation. More samples from varied seasonal, moisture and vegetation condition could be analysed and calibrated to the model for necessary improvement and that may fit to the local condition. However, the present model may contribute to improve existing erosion models and has direct applicability in field condition.

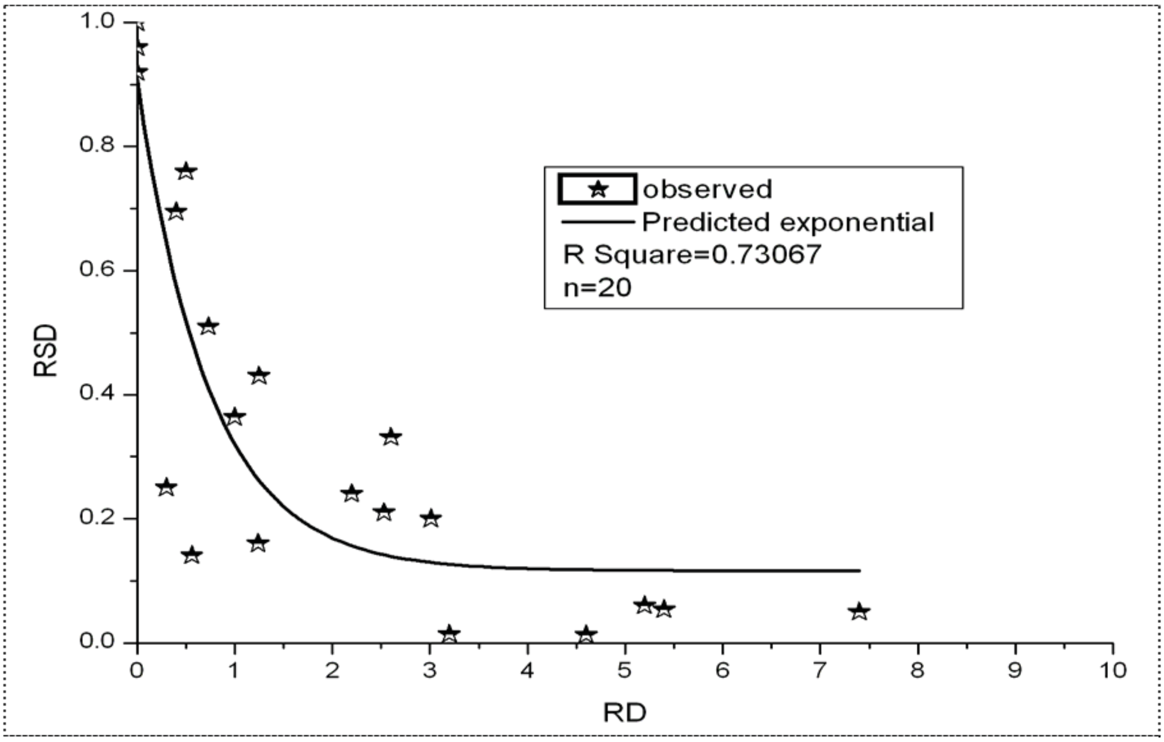

Figure 4. Relationship between root density (RD) and relative soil detachments (RSD).

Table 2. RD, ASD and RSD for topsoil samples at 25 degree slope gradient.

Resistance against concentrated flow erosion (Roots indicators)	Bare soils		Scatter grass roots topsoils		Densely grass roots topsoils	
	Mean	SD	Mean	SD	Mean	SD
RD (kg kg/m-3)	-	-	2.093	0. 2978	4.36	0. 585
ASD (kg m-2 s-1)	0.00592	0.00312	0.00528	0.00302	0.00363	0.00077
RSD	1	-	0.85636	0.05997	0.61739	0.1021

Table 3. RD, ASD and RSD for topsoil samples at 35 degree slope gradient.

Resistance against concentrated flow erosion (Roots indicators)	Bare soils		Scatter grass roots topsoils		Densely grass roots topsoils	
	Mean	SD	Mean	SD	Mean	SD
RD (kg kg/m-3)	-	-	2.124	0. 3183	4.87	0. 674
ASD (kg m-2 s-1)	0.0169	0.0151	0.00823	0.0039	0.0041	0.0017
RSD (35 degree slope)	1	-	0.57980	0.13088	0.13088	0.1073

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