Hydromulch roots reduce rill detachment capacity by overland flow in deforested hillslopes

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Hydromulch roots reduce rill detachment capacity by overland flow in deforested hillslopes

Abstract

Deforestation, which removes soil protection by plant leafs and roots, causes severe soil erosion, since the beneficial effects of plant cover and root actions on soil erodibility are lost. Hydromulching has been found to be a suitable technique for erosion control, but little research has been carried out to evaluate the effectiveness of hydromulch roots in controlling rill erosion in deforested areas due to overland flow. This study has evaluated rill detachment capacity (D_c) and erodibility (K_r, which is the slope of the equation regressing D_c and critical shear stress) in hydromulched and bare plots (1.3-m long and 0.5-m wide) on soils sampled in deforested hillslopes of Northern Iran; the most important root parameters of the grass used for hydromulching were also measured, such as root density and diameter. D_c has been measured in a laboratory flume under four bed slopes (10, 15, 20, and 25%) and five water discharges (0.26, 0.35, 0.45, 0.56, and 0.67 L m^{-1} s^{-1}) with five replications per experiment. D_c was lower (on average - 44%, with a minimum reduction of -40% at a slope of 25% and a maximum -50% at a slope of 15%) in the hydromulched soils compared to the untreated plot. D_c was positively and negatively correlated, with diameter and density of hydromulch roots, respectively. Rill erodibility was noticeably lower (-81%) in the hydromulched soil compared to the bare plot. By regressing D_c on shear stress, rill erodibility and critical shear stress for deforested hillslopes (treated with hydromulching or left bare) were given. These parameters are useful to hydrologists in applications of physically-based erosion models.

Keywords: deforestation; rill erosion; erosion control; root weight density; root diameter; rill erodibility; shear stress.

1. Introduction

Deforestation and inappropriate forest management practices are important reasons of soil erosion (one of the most serious problem in the global environment, Zhao et al. 2019) and, more generally, of degradation of its quality (Lucas-Borja et al. 2019; Shabanpour et al. 2020). When the vegetal cover of forests is removed, runoff generation and soil erosion increase (FAO 2000; Cherubin et al. 2017; Parhizkar et al. 2020). These processes produce heavy impacts on forest ecosystems (e.g. loss of biodiversity and productivity) (Decaëns et al. 2018; Lucas-Borja and Delgado-Baquerizo 2019) and surrounding environments (e.g. increased risks of flooding and infrastructure burial) (Bradshaw et al. 2007).

Soil erosion is a physical process that consists of detachment, transport and deposition of soil particles (Nearing et al. 1989). The initial phase of this complex process is detachment of particles from the soil matrix due to raindrop impact or overland flow (Govers et al. 1990; Aksoy and Kavvas 2005; Jiang et al., 2020). Soil particle detachment due to overland flow is different for inter-rill and rill erosion processes (Zhang et al. 2003). Rill erosion is the most important erosive process on steep slopes (Owoputi et al. 1995; Wang et al. 2004b), where the erosion rates are generally higher compared to slopes with gentler profile (Zhang et al. 2002). Moreover, rill development noticeably increases soil erosion rate and gully initiation with important implications on loss of fertile land and environmental impacts also on human settlements (Chaplot, 2013; Bryan and Rockwell, 1998; Shen et al., 2016; Dube et al., 2020). The maximum value of soil detachment due to rill erosion is known as “rill detachment capacity” (Foster 1982; Govers et al. 2007; Wang et al. 2016; Zhang et al. 2009; Liu et al., 2019; Zhou et al. 2019). This is an important parameter for estimating rill erosion rate (Shen et al., 2019). Although rill erosion has been widely investigated in the last decades, the study of this process and its influencing factors are still unclear (Shen et al., 2016). Moreover, the effects of concentrated flow erosion have received limited attention in literature (Dube et al. 2020).

Limiting soil detachment capacity by effective management practices is a key action to reduce the overall erosion rates, since a low detachment capacity, leaving soil particles in their original location, decreases the amount of solid material that can be transported downstream by the overland flow. The land management practices reducing soil detachment capacity are necessary in all environments and are of with particular importance in those deforested areas that are more exposed to runoff and soil erosion. Soil mulching, which consist of covering bare soil with a protective layer (mulch) of organic (e.g., crop residues) or inorganic (e.g., gravel, plastic micro-elements) materials (Patil Shirish et al. 2013; Prats et al. 2017), has been found cheap and sustainable to limit runoff and erosion due to overland flow (Prosdocimi et al. 2016). With regard to the organic mulch, materials such as hay, wood chips, shredded paper, grass and wood fibers have shown different levels of effectiveness in controlling soil erosion (Scholl et al. 2012; Ricks et al. 2020) and even improving several soil properties (de Lima et al. 2019). However, soil conservation is most efficient when mulching is used in conjunction with living plant species (Tyner et al. 2011). Moreover, mulching practices not only should be able to protect soil from detachment (Ettbeb et al. 2020), but should also enhance growth and survival of new plants. Mulching with these functions would be ideal to prevent soil erosion in delicate ecosystems (McCullough and Endress 2012), where the vegetal cover and plant biodiversity are scarce (Parhizkar et al. 2020). This is the case of hydromulching, a viable practice that has been very successfully used to rehabilitate degraded soil in the whole world. Theoretically, hydromulching consists of spraying a slurry of seed, water, fertilizer, binding agents, super-absorbents, fiber mulch and green dye on soil surface (Bautista et al. 2009; Dodson and Peterson 2009; Parsakhoo et al. 2018a). Hydromulch creates an absorbent layer by the sprayed fertilizers and grass seeds on the soil surface, and has a strong influence on runoff and erosion rates (Holt et al. 2005; Babcock and McLaughlin 2013; Ricks et al. 2020). It is well known how a grass cover of soil reduces runoff and soil loss (Li et al. 2011), trapping sediments transported by the surface runoff as a mechanical barrier (Parsakhoo et al. 2018b). Moreover, a root mat is formed by grasses in hydromulched soil (Fox et al. 2010) and these roots greatly reduced soil detachment capacity (Wang et al. 2018a; 2018b; Parhizkar et al. 2020). The application of hydromulch on soil surface is therefore effective for soil conservation (Ricks et al. 2020; Parsakhoo et al. 2018a) and beneficial for vegetation recovery (Lucas-Borja et al. 2020).

Several studies have reported how and by what extent hydromulching can effectively reduce water runoff and soil erosion (Prats et al. 2013; Ricks et al. 2020; Ettbeb et al.

2020). For instance, Eck et al. (2010) showed that hydromulching reduced the sediment yield by about 75% in comparison with bare plots at a quarry in Parker County (USA). Parsakhoo et al. (2018a) applied hydromulch and several herbal seeds to artificial soil slopes of forest roads in Iran, showing significant reduction (by at least 50%) in soil erosion rates compared to non-mulched plots. According to McLaughlin and Brown (2006), hydromulching based on addition of polyacrylamide reduces water turbidity and soil loss by about 85% in comparison to bare soil.

Despite the abundant literature about the effects of hydromulching on soil erosion, the studies focusing its effectiveness in controlling rill erosion when applied in deforested areas are lack. Rill erosion due to overland flow is the most important erosive process on steep slopes (Owoputi et al. 1995; Wang et al. 2014b), and its control is essential after deforestation. Moreover, information regarding the effects of hydromulch roots on rill detachment capacity and erodibility is scarce. To fill this gap, this study evaluates the changes in rill detachment capacity due to hydromulching in deforested hillslopes. More specifically, the rill detachment capacity of soils subjected to hydromulching or left bare was measured in a laboratory flume at different water discharges and bed slopes. Moreover, the root characteristics of the hydromulch that mostly influence rill detachment capacity were analyzed. Moreover, regression models are suggested to predict rill erodibility from soil detachment capacity on both hydromulched and bare soils. The quantitative data and prediction models obtained in this study can provide insights about the effectiveness of hydromulching in deforested lands, where the need for soil conservation is mandatory.

2. Materials and methods

2.1. Study area

The study was carried out on soil samples collected in a forestland of Guilan province (Northern Iran), located near Rasht city (geographic coordinates 37°08′04″ N - 49°39′44″ E) (Figure 1).

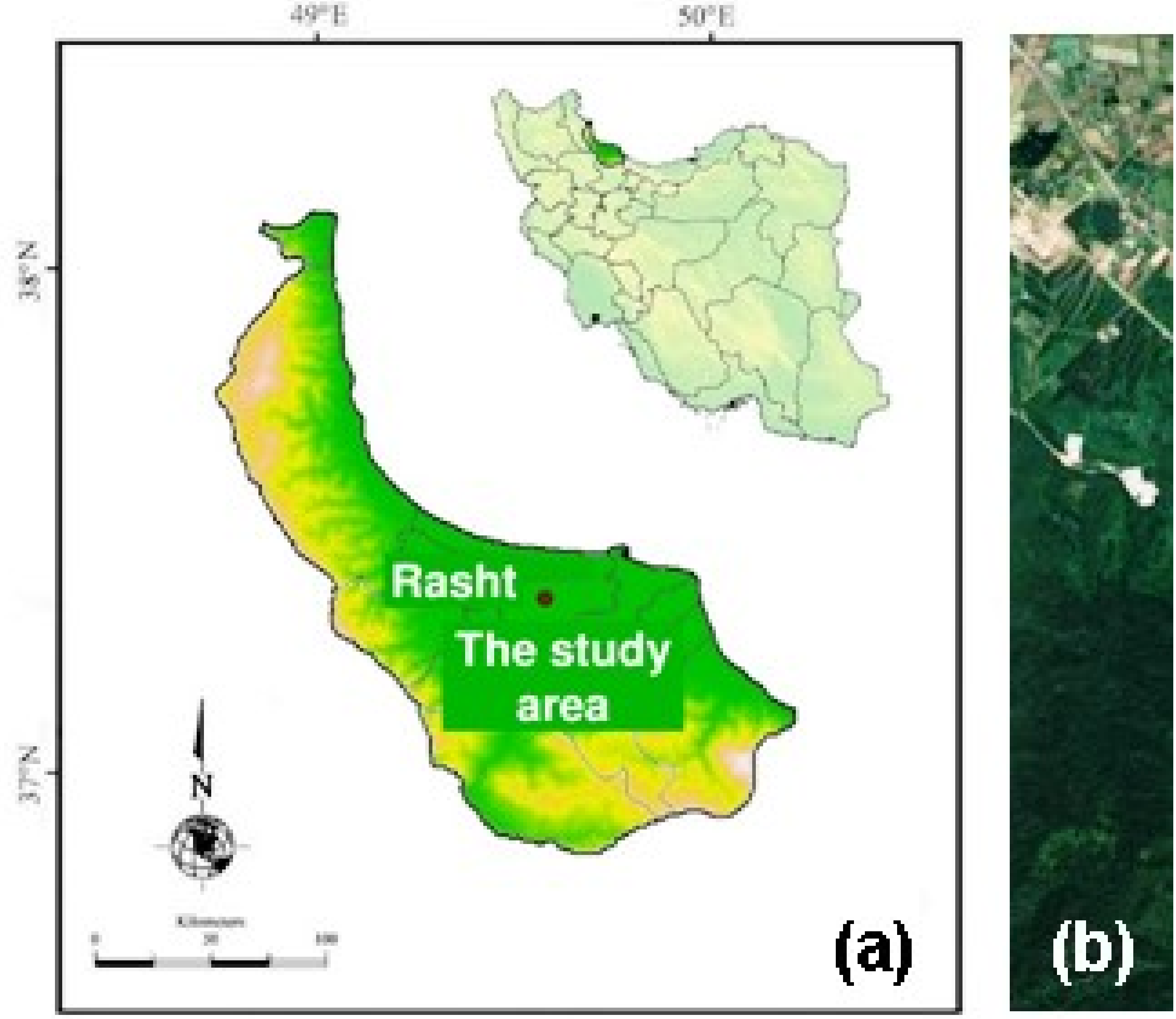


Figure 1 - Geographical location (a), aerial map of study area (b), and image of a deforested hillslope (c) (source: Google® Map®) (Guilan province, Northern Iran).

Deforestation has been severe for many years in the forest areas of Northern Iran (Kelarestaghi 2006; Gholoubi et al. 2019; Parhizkar et al. 2020a). Several hillslopes in this area were deforested to install high-voltage power towers and deforestation has determined the loss of almost all the vegetation (Parhizkar et al. 2020b; 2020c). The loss of biodiversity and increase in soil erosion have been the most important consequences of deforestation.

The deforested site, selected in this study because of its susceptibility to rill erosion (Parhizkar et al. 2020c), has an elevation ranging from 50 to 250 m above the mean sea level. The area has a typical Mediterranean climate, Csa type, according to the Köppen-Geiger classification (Kottek et al. 2006). The mean annual temperature and precipitation are 16.3 °C and 1360 mm, respectively (IRIMO 2016).

The soil has a silty clay loam texture (SDSD, 2017) with sand, silt and clay contents of 12.8 ± 0.44%, 47.8 ± 0.46%, 39.3 ± 0.21%, respectively. The organic matter content is 1.94 ± 0.36%, while the bulk density is 1554 ± 61.7 kg m^{-3} and aggregate stability in water is 0.96 ± 0.18 (n = 24 samples, measurement methods reported in Parhizkar et al., 2020c).

2.2. Soil sampling and plot preparation

Samples of deforested soils were randomly collected from the top layer (0 to 20 cm) between June and September 2019, according to the procedure by Geng et al. (2017). Litter, weeds, and rocks were removed from soil before sampling. Then, the samples were collected and transported to the Soil Testing laboratory of the College of Agriculture, Guilan University, Iran. Here, the soil was air-dried and sieved through a 2-mm mesh.

The sampled soil was placed in two experimental plots, made of timber planks (length of 1.3 m and width of 0.5 m) with 0.1-m high sides (Shoemaker 2009; Singh Sidhu 2015; Ricks et al. 2020). The soil of the first plot was subjected to hydromulch spraying on the surface (Figure 2a), while the first plot was left bare and assumed as control. This allows the comparison between deforested, and hydromulched or bare soils. Then, the soil was wetted until saturation and maintained under a tarpaulin cover for 24 h (Geng et al. 2017).

2.3. Hydromulch characteristics and application methods

Hydromulch material was produced using a mixture of water, grass seed, organic binder, starter fertilizer, cellulose fiber, bio-humus, super absorbent, and green dye. These native materials were blended in the mixture according to the hydromulching international protocol (Sheldon and Bradshaw 1997; Albaladejo Montoro et al. 2000; Fox et al. 2010; Parsakhoo et al. 2018a). Seeds of *Zoysia* grass, which is a grass growing in the warm season and has a deep root system (Beiraghdar et al., 2014), were selected for this study. The hard leaves and deep roots of this grass make a dense vegetal cover on the soil surface (Soroush et al. 2008). Organic materials were added to the hydromulch as binding agents of soil particles, in order to stabilize the soil aggregates (Sheldon and Bradshaw 1997; Parsakhoo et al. 2018a). To enhance the germination rapidity of the grass seeds, cellulose fiber and bio-humus, as absorbent mats, were also used (Holt et al. 2005; Dodson and Peterson 2009; Babcock and McLaughlin 2013). Finally, starter fertilizer and super absorbent were added to provide food for the growing seedlings and increase the water-holding capacity of soil, respectively (Parsakhoo et al. 2018b; Abdallah et al. 2019). According to the doses used in previous works, properly scaled to consider the size of the plots (Holt et al. 2005; Ricks et al. 2020), the hydromulch was applied at 410 kg ha^{-1} in 4 L water.

Figure 2 - The plots with bare soil (A) and hydromulch (after grass growth) (B) (Parhizkar et al. 2020b), and the experimental flume (C) (Parhizkar et al. 2020a; 2020b; 2020c) used to measure rill detachment capacity in deforested hillslopes of Guilan province (Northern Iran).

2.4. Soil sampling in hydromulched plots and characterisation of hydromulch roots

Once grass grew in the hydromulched plots (Figure 2b), its leaves were removed from the soil surface using scissors. Then, the soil samples were extracted along with their roots using a steel ring (diameter of 0.1 m and height of 0.05 m) (Parhizkar et al. 2020a; 2020b; 2020c; Khanal and Fox 2017). An additional hydromulched plot with the same characteristics as above was used to measure the grass root characteristics. The roots were sampled from different parts of this plot after six months from planting, and twenty samples were achieved (see section 2.7). The diameter, length, biomass and weight density of grass roots were measured. The length and diameter were determined using a universal tape meter and a Vernier caliper, respectively. To measure the root biomass, the samples were first oven-dried at 60 °C for 48 h. Then, the dried samples were weighted for several times until a constant value. Root weight density was measured by the washing method over a 1-mm sieve and subsequent oven-drying (at 65 °C for 24 h).

2.5. Simulation of rill detachment by overland flow

Rill detachment was simulated on samples collected in both plots (deforested and hydromulched as well as deforested and bare soils) using a hydraulic flume (length of 3.5 m) with a rectangular cross section (width of 0.2 m) (Figure 2c). The soil was collected from each plot using a steel ring with diameter of 0.1 m and height of 0.05 m). Then, the sample surface was sprayed with water and then inserted in the flume bed after excavating a hole of the same size as the ring about 0.5 m upstream of its outlet. Then, the bed slope of the flume was adjusted at the desired value and the water discharge was set (see section 2.7), dosing water into the flume from an upstream tap. The water discharge was measured in five replications using a graduated cylinder. Moreover, the surface water velocity was determined measured in ten replications using the fluorescent dye technique. The average value was the product of the measured water velocity by coefficients of 0.6, 0.7 or 0.8, for laminar, transitional or turbulent flow, respectively (Abrahams et al. 1985). A level probe (accuracy of 1 mm) was used to measure the water depth. This measurement was carried out in six replications in two cross sections (0.4 m and 1 m from the flume outlet) and three points per section (in the center as well as at 0.01 m from the left and right sides of the flume).

Each experiment was stopped when the depth of the eroded soil in the steel ring was 0.015 m or after five minutes. After each experiment, the soil dry weight was determined oven drying the wet soil sample for 24 h at 105 °C. More details about the flume characteristics and the experimental procedure can be found in Parhizkar et al. (2020a; 2020b; 2020c).

2.6. Measurement of rill detachment capacity and erodibility

The mean rill detachment capacity (D_c, kg s^{-1} m^{-2}) was calculated by averaging the individual values of the replicated experiments for each water discharge and bed slope of the flume using equation (1):

$$D_c = \frac{\Delta M}{A \cdot \Delta t} \quad (1)$$

In Eq. 1, ΔM is the dry weight of detached soil (kg), A is the area of the soil sample (m^2) and Δt is experiment duration (s).

Rill erodibility (K_r, s m^{-1}) and critical shear stress (τ_c, Pa) are important parameters used as input in process-based erosion models (Wang et al. 2016), such as the Water Erosion Prediction Project (WEPP) (Nearing et al. 1989). Both parameters are indicators of soil resistance to rill erosion.

In this study, rill erodibility and critical shear stress were calculated from the regression equation (2) that interpolates shear stress (τ, Pa, Foster, 1982) and rill detachment capacity:

$$D_C = K_r(\tau - \tau_c) \qquad (2)$$

K_r and τ_c are the slope and intercept of Eq. (2).

Shear stress was calculated in accordance with equation (3), proposed by several authors (Nearing et al., 1997):

$$\tau = \rho g R S \qquad (3)$$

In this equation, R is the hydraulic radius (m), ρ is the water density (kg m^{-3}), g is the gravity acceleration (m s^{-2}) and S is the bed slope [m m^{-1}] (Parhizkar et al., 2020a). The hydraulic radius is calculated by equation (4):

$$R = \frac{h \cdot p}{2p + h} \qquad (4)$$

where h is the depth and p is the width of the water flow (in m).

Table 1SD shows the values of h, R and τ of the experiments simulating the rill detachment process at each water discharge and bed slope in the flume.

2.7. Experimental design

An experiment of rill detachment was simulated for each soil condition (deforested and bare soil, hereinafter DB, and deforested and hydromulched soil, DH) at five water discharges (0.26, 0.35, 0.45, 0.56, and 0.67 L m^{-1} s^{-1}) and four bed slopes (10%, 15%, 20%, and 25%). The latter values are similar to the slopes of the forests of the experimental area (between 7-8% and 20-22% or slightly more). Each experiment consisted of five replicates. Overall, 200 soil samples (2 condition × 5 water discharges × 4 bed slopes × 5 replications) were subjected to rill detachment simulation.

Data of hydromulch root characterization were coupled to data of flume experiment as follows. The 100 soil samples for flume experiment (one for each of five water discharges and four bed slopes, each in five replications) were collected from the first hydromulched plot. As many samples were collected from the second hydromulched plot for root characterization, choosing the same positions as the previous samples. All pairs of samples were marked for identification. Twenty composite samples of soil collected in the second plot were achieved, by mixing the five samples for each water discharge and bed slope.

2.7. Statistical analysis

A paired sample t-test evaluated the statistical significance of the differences in the rill detachment capacity (dependent variable) between soil conditions (independent variables) at p-level < 0.05. The normality of sample distribution was checked using QQ-plots; when the assumptions of the statistical tests were not satisfied, the data were square root transformed. Pearson's matrix was calculated to identify possible correlations among D_c and the root characteristics of hydromulch. All statistical analyses were carried out using XLSTAT 9.0 software (Addinsoft, Paris, France).

3. Results

3.1. Characteristics of hydromulch roots

The soil samples contained hydromulch roots with a diameter between 0.61 and 0.79 mm with an average value of 0.69 ± 0.06 mm (Table 1). The root length was in the range 12.6 - 22.5 cm, while its mean was equal to 17.3 cm. The mean root biomass was 22.29 ± 3.08 g, while the lowest and highest values were 17.12 and 27.73 g. The root weight density was between 0.31 and 0.76 kg m^{-3}; its mean value was 0.54 ± 0.12 kg m^{-3} (Table 1).

Table 1 - Main statistics of root characteristics in samples (n = 20) of hydromulched hillslopes (Guilan province, Northern Iran).

Root characteristics	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**
Diameter (mm)	0.69	0.61	0.79	0.06
Length (cm)	17.29	12.58	22.46	3.19
Biomass (g)	22.29	17.12	27.73	3.08
Weight density (kg m^{-3})	0.54	0.31	0.76	0.12

3.2. Variations of rill detachment capacity between soil conditions

The rill detachment capacity in DH soils was significantly ($p < 0.05$) lower compared to the DB plot. As shown in Figure 3, D_c was on the average 0.027 kg m^{-2} s^{-1} in DH plots, a 1.5-fold value compared the DB soils (0.047 kg m^{-2} s^{-1}). Also, the variability of D_c was lower in DH soils, as shown by the lower standard deviation (0.013 kg m^{-2} s^{-1} vs. 0.024 kg m^{-2} s^{-1} measured in the DB plot) (Figure 3).

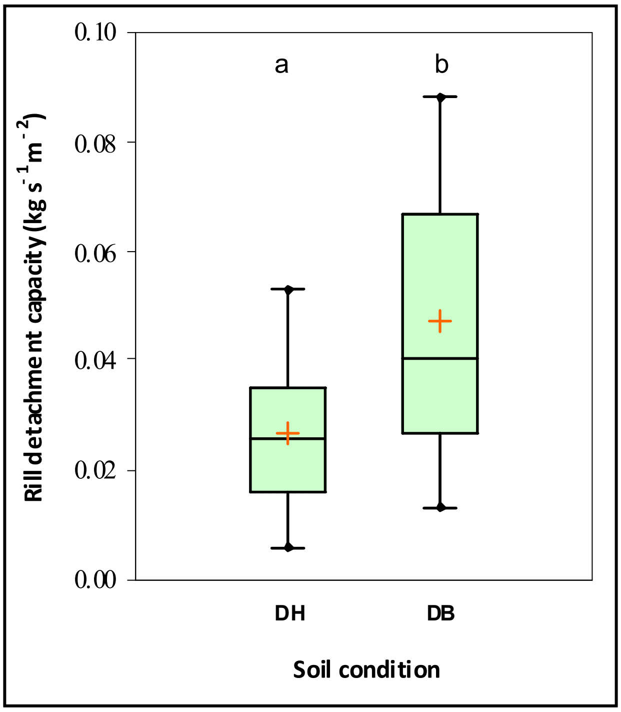


Figure 3 - Box plots of rill detachment capacity of hydromulched (DH) and bare soils (DB) in deforested hillslopes of Guilan province (Northern Iran). Different lowercase letters indicate significant differences ($p < 0.05$) between deforested and hydromulched (DH), and deforested and bare (DB) plots.

3.2. Analysis of the relationships between rill detachment capacity and root characteristics

The Pearson's matrix shows that D_c was positively correlated with root diameter ($r = 0.593$) ($p < 0.05$), and negatively correlated with root weight density ($r = -0.566$) ($p < 0.05$). A negative correlation, but not significant ($p < 0.05$), was also found between diameter and weight density of hydromulch roots ($r = -0.529$) (Table 2).

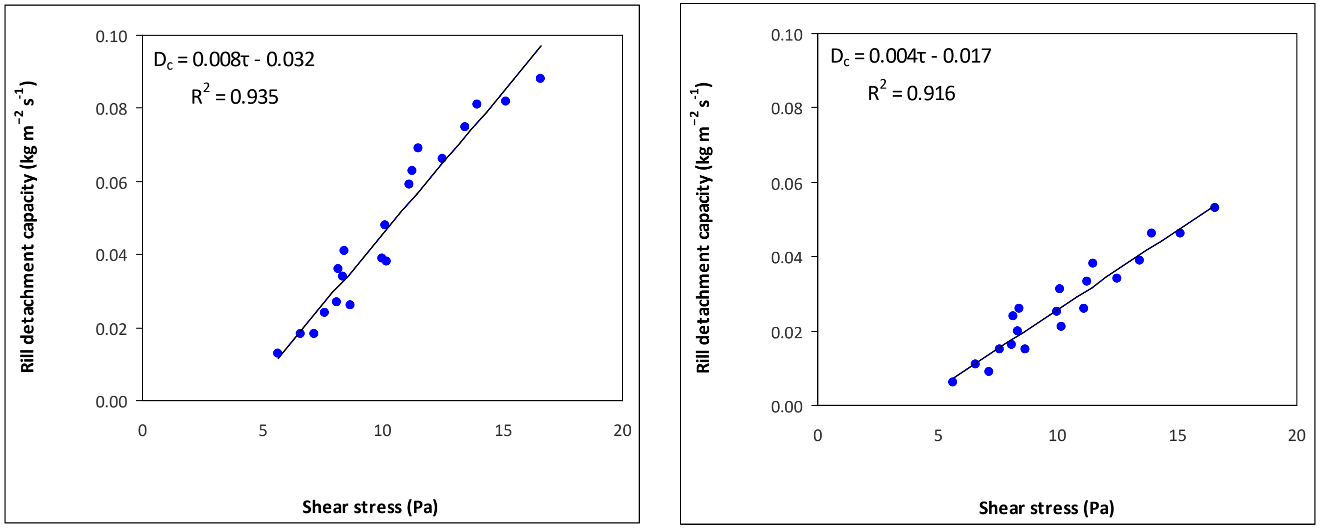
Table 2 - Pearson's correlation matrix of rill detachment capacity and root characteristics in deforested hillslopes plots treated with hydromulch (Guilan province, Northern Iran).

Original variables		***Rill detachment capacity***	***Root characteristics***			
			diameter	***length***	***biomass***	***weight density***
Rill detachment capacity		**1**	**0.593**	-0.088	-0.047	**-0.566**
Root characteristics	***diameter***		**1**	-0.054	0.110	-0.529
	length			**1**	0.293	0.048
	biomass				**1**	0.028
	weight density					**1**

Notes: values in bold are significant at $p < 0.05$.

3.3. Relationships between rill detachment capacity and shear stress and estimation of rill erodibility

The regression analysis applied to D_c and τ using equation (2) showed that the slope (K_r) and intercept (τ_c) of the interpolating lines were different between DH and DB soils. The coefficient of determination (R^2) of the regression models was over 0.90 (0.93 and 0.92 for DB and DH soil, respectively), and always significant at $p < 0.05$ (Figure 4). K_r was higher in DB soil (0.0078 s m^{-1}) compared to DH plot (0.043 s m^{-1}), while τ_c was higher in DH soils (4.11 Pa) and lower in DB plots (3.91 Pa) (Figure 4).



(a) (b)

Figure 4 - Scatterplots of rill detachment capacity (D_c) estimated from shear stress (τ) using the linear regression models in deforested and bare (a), and deforested and hydromulched (b) soils (Guilan Province, Northern Iran).

4. Discussions

4.1. Influence of hydromulching on rill detachment capacity

In this study, the deforested soils subjected to hydromulching or left bare had the same characteristics (such as the soil type and texture) and experienced the same water discharges and bed slopes in the experiments. Therefore, the effects of hydromulching and, especially, the root characteristics can explain alone the changes in rill detachment capacity and erodibility between the treatment and the control plots. Previous studies have demonstrated that the conservation techniques based on hydromulching are able to significantly reduce soil loss in several environmental conditions (e.g., Hubbert et al. 2012; Prats et al. 2013; Parsakhoo et al. 2018a; Ricks et al. 2020). The results of the experiments carried out in the current investigation are in accordance to these studies. As a matter of fact, hydromulching reduced on the average rill detachment capacity by 44% compared to the bare soil, with a peak of 54% for the minimum values of rill detachment capacity. This reduction let us think that also soil loss, although not directly measured in these experiments, can be lower in hydromulched soils compared to bare soil. This reduction may be expected, since Robichaud et al. (2000) reported that hydromulching is able to control erosion in the short term, because its application enhances a vegetation cover with a dense root system. Conversely, other studies have demonstrated that the vegetal cover might be insignificant for the prevention and control of rill erosion (De Baets et al. 2007; Wang et al. 2014a).

The correlation analysis helps to explain which characteristics of the hydromulch roots play a greater influence on the observed reduction in rill detachment capacity. This statistical technique has identified significant correlations between rill detachment capacity on one side and weight density and diameter of roots on the other side. More specifically, when root weight density decreases, rill detachment capacity increases. Root weight density is an important indicator of the ability of plants at reducing soil detachment (Yoshinorui et al. 2016; Parhizkar et al., 2021a). Conversely, in soils with higher root diameter, rill detachment capacity is higher. Also other studies have found positive correlations between some parameters related to soil resistance to concentrated erosion and root characteristics (e.g., Li et al. 1992; Wang et al. 2015; Wang and Zhang 2017).

The reduction in rill detachment capacity measured in deforested and hydromulched soils may be ascribed to two factors, that is, weight density and diameter of roots in vegetation cover.

First, it is well known that soils with a prominent vegetation cover show higher root weight density (Parhizkar et al. 2020c; in press). This parameter, identified by the correlation analysis among the root characteristics that mostly influence rill detachment capacity determines a beneficial effect, reducing soil detachability (Li et al. 2015) and thus on soil's resistance to particle detachment. The direct association between rill detachment capacity and root weight density is in accordance with findings of many authors (e.g., Zhang et al. 2013; Li et al. 2015; Wang et al. 2015). These studies state that increases in root weight density are effective in reducing the soil detachability. Among the other studies reporting similar impacts of the plant roots in reducing soil detachment (e.g., Li et al. 1991; Li 1995), and specifically in controlling rill erosion (Gyssels et al. 2005), it is interesting to notice that Zhang et al. (2013) reported an exponential decrease in soil detachment capacity with the increase in root weight density. However, this law has not been confirmed in our study, which found a coefficient of determination of only 0.20 in regressing rill detachment capacity with root weight density (data not shown).

Second, the root diameter is the other characteristic of root hydromulch that mostly influences rill detachment capacity in the hydromulched soil. Root diameter was lower than one mm in all experiments, and this size was effective in reducing rill detachment capacity compared to the bare soil without grass roots. This size is in accordance with findings of many authors (e.g., De Baets et al. 2006, 2007; Loades et al. 2010; Leung et al. 2015; Li et al. 2015), who reported that roots with diameter less than one mm are effective in controlling concentrated flow and protecting soil from rill detachment, with clear reduction in hillslope erodibility. Conversely, Khanal and Fox (2017) showed that erosion rates at high shear stress decrease with increasing root diameter.

Unexpectedly, the influence of the other root characteristics, length and biomass, on rill detachment capacity was not evidenced by this study. The scarce influence of root length on soil erodibility may be justified by the fact that the detachment of soil particles is a surface process, whereas grass roots mainly penetrate in the sub-surface layer of soil rather than extending on its surface (Yoshinori et al. 2016). The absence of biomass effects on soil detachability can be explained by the low time elapsed from the hydromulch application to the experiment. Organic matter supplied by biomass needs more time to degrade and play beneficial effects on soil structure, such as aggregation properties (Lucas-Borja et al. 2018). The role of these factors can be instead expected in other land uses different from deforested areas. For example, Parhizkar et al. (2020a) reported that vegetation cover with the effects of its roots can help to reduce soil detachment in forestland and woodland of Northern Iran.

4.2. Influence of hydromulching on rill erodibility

Literature studies have clearly demonstrated that rill detachment rate and erodibility depend on plant root characteristics (Mamo and Bubenzer 2001a, 2001b; De Baets and Poesen 2010; Gyssels et al. 2006). As shown for rill detachment capacity, this study has demonstrated that grass roots are able to decrease rill erodibility in hydromulched soils. For bare soil, rill erodibility was 1.8 times greater than the value of the hydromulched plot, while the ratio of τ_c measured in DB and DH soils was close to one. This result is consistent with the studies by Mamo and Bubenzer (2001a; 2001b), who found that rill erodibility decreases by an exponential law in soils with living plant root. Moreover, Li et al. (1991) showed that the decrease in rill detachment capacity and erodibility of soil under concentrated flow is more pronounced, if roots have a diameter lower than one mm (as in this study) and this root size is known as “effective” root diameter.

The regression model between rill detachment capacity and shear stress proposed in this study is very accurate for both bare and hydromulched soils ($R^2 > 0.90$). This is accuracy is in close accordance with Zhang et al. (2008), who found coefficients of determination up to 0.90 for equations interpolating rill detachment capacity and shear stress under different land uses.

It is interesting to note that the erodibility estimated for the hydromulched plot is lower compared to the values measured in grasslands in a previous work (Parhizkar et al. 2020a). This can be explained by the disturbance effects on the deforested soils on

which rill erodibility was estimated in the current experiments. This result is consistent with the findings of Zhang (2003), who demonstrated that disturbed soils can be more easily detached under overland flow, due to the destruction of soil structure.
The values of rill erodibility and critical shear stress suggested by the present study are useful to help land managers to simulate the hydrological impacts of soil conservation measures, such as hydromulch application in deforested areas, in order to reduce the erosion risk. As a matter of fact, rill erodibility and critical shear stress are the most important parameters reflecting the soil resistance to rill erosion (Nearing et al. 1989). Therefore, accurate values for these parameters are essential to achieve reliable predictions of erosion by applying physically-based erosion models (Wang et al. 2016), such as the Water Erosion Prediction Project (WEPP) (Laflen et al. 1991).

5. Conclusions

This study has evaluated rill detachment capacity in hydromulched and untreated plots through flume experiments on soils sampled in deforested hillslopes of Northern Iran. Rill detachment capacity in the hydromulched soil was significantly lower compared to the bare plot. D_c was positively and negatively correlated with diameter and density of hydromulch roots, respectively. Rill erodibility was noticeably lower (-81%) in the hydromulched soil compared to the bare plot. These outcomes show the effectiveness of hydromulch roots with lower diameter and higher weight density in reduceing rill detachment capacity. Moreover, by regressing rill detachment capacity on shear stress upon the measurements, rill erodibility and critical shear stress for deforested hillslopes (treated with hydromulching or left bare) were given. These regression models and values help hydrologists in applications of erosion models to reduce erosion rates in deforested hillslopes.

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SUPPLEMENTARY DATA

Table 1SD - Flow characteristics in the experiments measuring the rill detachment capacity of hydromulched and bare soils in deforested hillslopes of Guilan province (Northern Iran).

Experiment	Slope (S, %)	Water discharge (q, L m^{-1} s^{-1})	Water depth (h, cm)	Hydraulic radius (R, m)	Shear stress (τ, Pa)
1		0.22	0.610	0.006	5.633
2		0.33	0.720	0.007	6.580
3	10	0.44	0.840	0.008	7.588
4		0.56	0.930	0.009	8.336
5		0.67	0.940	0.009	8.418
6		0.22	0.514	0.005	7.150
7		0.33	0.628	0.006	8.670
8	15	0.44	0.748	0.007	10.215
9		0.56	0.820	0.008	11.129
10		0.67	0.930	0.009	12.501
11		0.22	0.432	0.004	8.085
12		0.33	0.538	0.005	9.978
13	20	0.44	0.612	0.006	11.242
14		0.56	0.740	0.007	13.437
15		0.67	0.840	0.008	15.160
16		0.22	0.346	0.003	8.168
17		0.33	0.434	0.004	10.155
18	25	0.44	0.492	0.005	11.479
19		0.56	0.606	0.006	13.942
20		0.67	0.730	0.007	16.625