

## Università degli Studi Mediterranea di Reggio Calabria

Archivio Istituzionale dei prodotti della ricerca

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

This is the peer reviewd version of the followng article:

Original

Hydromulch roots reduce rill detachment capacity by overland flow in deforested hillslopes / Parhizkar, M.; Shabanpour, M.; Esteban Lucas-Borja, M.; Zema, D. - In: JOURNAL OF HYDROLOGY. - ISSN 0022-1694. -598:126272(2021). [10.1016/j.jhydrol.2021.126272]

Availability: This version is available at: https://hdl.handle.net/20.500.12318/123348 since: 2024-11-20T10:13:11Z

Published DOI: http://doi.org/10.1016/j.jhydrol.2021.126272 The final published version is available online at:https://www.sciencedirect.

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website

Publisher copyright

This item was downloaded from IRIS Università Mediterranea di Reggio Calabria (https://iris.unirc.it/) When citing, please refer to the published version.

(Article begins on next page)

1	This is the peer reviewed version of the following article:
2	
3	Parhizkar, M., Shabanpour, M., Lucas-Borja, M. E., & Zema, D. A. (2021).
4	Hydromulch roots reduce rill detachment capacity by overland flow in deforested
5	hillslopes. Journal of Hydrology, 598, 126272,
6	
7	which has been published in final doi
8	
9	10.1016/j.jhydrol.2021.126272
10	
11	
12	(https://www.sciencedirect.com/science/article/pii/S002216942100319X)
13	
14	The terms and conditions for the reuse of this version of the manuscript are specified in
15	the publishing policy. For all terms of use and more information see the publisher's
16	website

#### 17 Hydromulch roots reduce rill detachment capacity by overland flow in deforested

18

#### hillslopes

19

20 Abstract

21

22 Deforestation, which removes soil protection by plant leafs and roots, causes severe soil 23 erosion, since the beneficial effects of plant cover and root actions on soil erodibility are 24 lost. Hydromulching has been found to be a suitable technique for erosion control, but 25 little research has been carried out to evaluate the effectiveness of hydromulch roots in 26 controlling rill erosion in deforested areas due to overland flow. This study has evaluated rill detachment capacity (D<sub>c</sub>) and erodibility (K<sub>r</sub>, which is the slope of the 27 28 equation regressing D<sub>c</sub> and critical shear stress) in hydromulched and bare plots (1.3-m 29 long and 0.5-m wide) on soils sampled in deforested hillslopes of Northern Iran; the 30 most important root parameters of the grass used for hydromulching were also 31 measured, such as root density and diameter. D<sub>c</sub> has been measured in a laboratory 32 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<sup>-1</sup> s<sup>-1</sup>) with five replications per experiment.  $D_c$  was lower 33 (on average - 44%, with a minimum reduction of -40% at a slope of 25% and a 34 35 maximum -50% at a slope of 15%) in the hydromulched soils compared to the untreated 36 plot. D<sub>c</sub> was positively and negatively correlated, with diameter and density of 37 hydromulch roots, respectively. Rill erodibility was noticeably lower (-81%) in the hydromulched soil compared to the bare plot. By regressing D<sub>c</sub> on shear stress, rill 38 39 erodibility and critical shear stress for deforested hillslopes (treated with hydromulching 40 or left bare) were given. These parameters are useful to hydrologists in applications of physically-based erosion models. 41

42

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

#### 46 **1. Introduction**

47

48 Deforestation and inappropriate forest management practices are important reasons of 49 soil erosion (one of the most serious problem in the global environment, Zhao et al. 50 2019) and, more generally, of degradation of its quality (Lucas-Borja et al. 2019; 51 Shabanpour et al. 2020). When the vegetal cover of forests is removed, runoff 52 generation and soil erosion increase (FAO 2000; Cherubin et al. 2017; Parhizkar et al. 53 2020). These processes produce heavy impacts on forest ecosystems (e.g. loss of 54 biodiversity and productivity) (Decaëns et al. 2018; Lucas-Borja and Delgado-55 Baquerizo 2019) and surrounding environments (e.g. increased risks of flooding and 56 infrastructure burial) (Bradshaw et al. 2007).

57 Soil erosion is a physical process that consists of detachment, transport and deposition 58 of soil particles (Nearing et al. 1989). The initial phase of this complex process is 59 detachment of particles from the soil matrix due to raindrop impact or overland flow 60 (Govers et al. 1990; Aksoy and Kavvas 2005; Jiang et al., 2020). Soil particle 61 detachment due to overland flow is different for inter-rill and rill erosion processes 62 (Zhang et al. 2003). Rill erosion is the most important erosive process on steep slopes 63 (Owoputi et al. 1995; Wang et al. 2004b), where the erosion rates are generally higher 64 compared to slopes with gentler profile (Zhang et al. 2002). Moreover, rill development 65 noticeably increases soil erosion rate and gully initiation with important implications on 66 loss of fertile land and environmental impacts also on human settlements (Chaplot, 67 2013; Bryan and Rockwell, 1998; Shen et al., 2016; Dube et al., 2020). The maximum 68 value of soil detachment due to rill erosion is known as "rill detachment capacity" 69 (Foster 1982; Govers et al. 2007; Wang et al. 2016; Zhang et al. 2009; Liu et al., 2019; 70 Zhou et al. 2019). This is an important parameter for estimating rill erosion rate (Shen et 71 al., 2019). Although rill erosion has been widely investigated in the last decades, the 72 study of this process and its influencing factors are still unclear (Shen et al., 2016). 73 Moreover, the effects of concentrated flow erosion have received limited attention in 74 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

78 downstream by the overland flow. The land management practices reducing soil 79 detachment capacity are necessary in all environments and are of with particular 80 importance in those deforested areas that are more exposed to runoff and soil erosion. 81 Soil mulching, which consist of covering bare soil with a protective layer (mulch) of 82 organic (e.g., crop residues) or inorganic (e.g., gravel, plastic micro-elements) materials 83 (Patil Shirish et al. 2013; Prats et al. 2017), has been found cheap and sustainable to 84 limit runoff and erosion due to overland flow (Prosdocimi et al. 2016). With regard to 85 the organic mulch, materials such as hay, wood chips, shredded paper, grass and wood 86 fibers have shown different levels of effectiveness in controlling soil erosion (Scholl et 87 al. 2012; Ricks et al. 2020) and even improving several soil properties (de Lima et al. 88 2019). However, soil conservation is most efficient when mulching is used in 89 conjunction with living plant species (Tyner et al. 2011). Moreover, mulching practices 90 not only should be able to protect soil from detachment (Ettbeb et al. 2020), but should 91 also enhance growth and survival of new plants. Mulching with these functions would 92 be ideal to prevent soil erosion in delicate ecosystems (McCullough and Endress 2012), 93 where the vegetal cover and plant biodiversity are scarce (Parhizkar et al. 2020). This is 94 the case of hydromulching, a viable practice that has been very successfully used to 95 rehabilitate degraded soil in the whole world. Theoretically, hydromulching consists of 96 spraying a slurry of seed, water, fertilizer, binding agents, super-absorbents, fiber mulch 97 and green dye on soil surface (Bautista et al. 2009; Dodson and Peterson 2009; 98 Parsakhoo et al. 2018a). Hydromulch creates an absorbent layer by the sprayed 99 fertilizers and grass seeds on the soil surface, and has a strong influence on runoff and 100 erosion rates (Holt et al. 2005; Babcock and McLaughlin 2013; Ricks et al. 2020). It is 101 well known how a grass cover of soil reduces runoff and soil loss (Li et al. 2011), 102 trapping sediments transported by the surface runoff as a mechanical barrier (Parsakhoo 103 et al. 2018b). Moreover, a root mat is formed by grasses in hydromulched soil (Fox et 104 al. 2010) and these roots greatly reduced soil detachment capacity (Wang et al. 2018a; 105 2018b; Parhizkar et al. 2020). The application of hydromulch on soil surface is therefore 106 effective for soil conservation (Ricks et al. 2020; Parsakhoo et al. 2018a) and beneficial 107 for vegetation recovery (Lucas-Borja et al. 2020).

108 Several studies have reported how and by what extent hydromulching can effectively 109 reduce water runoff and soil erosion (Prats et al. 2013; Ricks et al. 2020; Ettbeb et al. 110 2020). For instance, Eck et al. (2010) showed that hydromulching reduced the sediment 111 yield by about 75% in comparison with bare plots at a quarry in Parker County (USA). 112 Parsakhoo et al. (2018a) applied hydromulch and several herbal seeds to artificial soil 113 slopes of forest roads in Iran, showing significant reduction (by at least 50%) in soil 114 erosion rates compared to non-mulched plots. According to McLaughlin and Brown 115 (2006), hydromulching based on addition of polyacrylamide reduces water turbidity and 116 soil loss by about 85% in comparison to bare soil.

117 Despite the abundant literature about the effects of hydromulching on soil erosion, the 118 studies focusing its effectiveness in controlling rill erosion when applied in deforested 119 areas are lack. Rill erosion due to overland flow is the most important erosive process 120 on steep slopes (Owoputi et al. 1995; Wang et al. 2014b), and its control is essential 121 after deforestation. Moreover, information regarding the effects of hydromulch roots on 122 rill detachment capacity and erodibility is scarce. To fill this gap, this study evaluates 123 the changes in rill detachment capacity due to hydromulching in deforested hillslopes. 124 More specifically, the rill detachment capacity of soils subjected to hydromulching or 125 left bare was measured in a laboratory flume at different water discharges and bed 126 slopes. Moreover, the root characteristics of the hydromulch that mostly influence rill 127 detachment capacity were analyzed. Moreover, regression models are suggested to 128 predict rill erodibility from soil detachment capacity on both hydromulched and bare 129 soils. The quantitative data and prediction models obtained in this study can provide 130 insights about the effectiveness of hydromulching in deforested lands, where the need 131 for soil conservation is mandatory.

132

- 133 **2. Materials and methods**
- 134

## 135 2.1. Study area

136

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).

- 140
- 141





Figure 1 - Geographical location (a), aerial map of study area (b), and image of a
deforested hillslope (c) (source: Google<sup>®</sup> Map<sup>®</sup>) (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  $\pm$  0.44%, 47.8  $\pm$  0.46%, 39.3  $\pm$  0.21%, respectively. The organic matter content is 1.94  $\pm$  0.36%, while the bulk density is 1554  $\pm$  61.7 kg m<sup>-3</sup> and aggregate stability in water is 0.96  $\pm$  0.18 (n = 24 samples, measurement methods reported in Parhizkar et al., 2020c).

- 162
- 163 2.2. Soil sampling and plot preparation
- 164

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 2mm 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).

178

# 179 2.3. Hydromulch characteristics and application methods

180

181 Hydromulch material was produced using a mixture of water, grass seed, organic 182 binder, starter fertilizer, cellulose fiber, bio-humus, super absorbent, and green dye. 183 These native materials were blended in the mixture according to the hydromulching 184 international protocol (Sheldon and Bradshaw 1997; Albaladejo Montoro et al. 2000; 185 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 186 187 selected for this study. The hard leaves and deep roots of this grass make a dense 188 vegetal cover on the soil surface (Soroush et al. 2008). Organic materials were added to 189 the hydromulch as binding agents of soil particles, in order to stabilize the soil 190 aggregates (Sheldon and Bradshaw 1997; Parsakhoo et al. 2018a). To enhance the 191 germination rapidity of the grass seeds, cellulose fiber and bio-humus, as absorbent 192 mats, were also used (Holt et al. 2005; Dodson and Peterson 2009; Babcock and 193 McLaughlin 2013). Finally, starter fertilizer and super absorbent were added to provide 194 food for the growing seedlings and increase the water-holding capacity of soil, 195 respectively (Parsakhoo et al. 2018b; Abdallah et al. 2019). According to the doses used 196 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<sup>-1</sup> in 4 L water. 197



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;
201 2020c) used to measure rill detachment capacity in deforested hillslopes of Guilan
province (Northern Iran).

205 Once grass grew in the hydromulched plots (Figure 2b), its leaves were removed from 206 the soil surface using scissors. Then, the soil samples were extracted along with their 207 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 208 209 characteristics as above was used to measure the grass root characteristics. The roots 210 were sampled from different parts of this plot after six months from planting, and 211 twenty samples were achieved (see section 2.7). The diameter, length, biomass and 212 weight density of grass roots were measured. The length and diameter were determined 213 using a universal tape meter and a Vernier caliper, respectively. To measure the root 214 biomass, the samples were first oven-dried at 60 °C for 48 h. Then, the dried samples 215 were weighted for several times until a constant value. Root weight density was 216 measured by the washing method over a 1-mm sieve and subsequent oven-drying (at 65 217 °C for 24 h).

218

# 219 2.5. Simulation of rill detachment by overland flow

220

Rill detachment was simulated on samples collected in both plots (deforested and 221 222 hydromulched as well as deforested and bare soils) using a hydraulic flume (length of 223 3.5 m) with a rectangular cross section (width of 0.2 m) (Figure 2c). The soil was 224 collected from each plot using a steel ring with diameter of 0.1 m and height of 0.05 m). 225 Then, the sample surface was sprayed with water and then inserted in the flume bed 226 after excavating a hole of the same size as the ring about 0.5 m upstream of its outlet. 227 Then, the bed slope of the flume was adjusted at the desired value and the water 228 discharge was set (see section 2.7), dosing water into the flume from an upstream tap. 229 The water discharge was measured in five replications using a graduated cylinder. 230 Moreover, the surface water velocity was determined measured in ten replications using 231 the fluorescent dye technique. The average value was the product of the measured water 232 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).

242

### 243 2.6. Measurement of rill detachment capacity and erodibility

244

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

248

$$249 D_c = \frac{\Delta M}{A \cdot \Delta t} (1)$$

250

In Eq. 1,  $\Delta M$  is the dry weight of detached soil (kg), A is the area of the soil sample (m<sup>2</sup>) and  $\Delta t$  is experiment duration (s).

Rill erodibility ( $K_r$ , s m<sup>-1</sup>) and critical shear stress ( $\tau_c$ , 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 ( $\tau$ , Pa, Foster, 1982) and rill detachment capacity:

$$261 D_c = K_r(\tau - \tau_c) (2)$$

262  $K_r$  and  $\tau_c$  are the slope and intercept of Eq. (2).

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

265

267

In this equation, R is the hydraulic radius (m),  $\rho$  is the water density (kg m<sup>-3</sup>), g is the gravity acceleration (m s<sup>-2</sup>) and S is the bed slope [m m<sup>-1</sup>] (Parhizkar et al., 2020a). The hydraulic radius is calculated by equation (4):

271

$$272 \qquad R = \frac{h \cdot p}{2p + h} \tag{4}$$

273

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

275

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

278

279

280 2.7. Experimental design

281

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<sup>-1</sup> s<sup>-1</sup>) 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. 289 Data of hydromulch root characterization were coupled to data of flume experiment as 290 follows. The 100 soil samples for flume experiment (one for each of five water 291 discharges and four bed slopes, each in five replications) were collected from the first 292 hydromulched plot. As many samples were collected from the second hydromulched 293 plot for root characterization, choosing the same positions as the previous samples. All 294 pairs of samples were marked for identification. Twenty composite samples of soil 295 collected in the second plot were achieved, by mixing the five samples for each water 296 discharge and bed slope.

297

298

2.7. Statistical analysis

299

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).

- 307
- 308 **3. Results**

309

311

The soil samples contained hydromulch roots with a diameter between 0.61 and 0.79 mm with an average value of  $0.69 \pm 0.06$  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  $\pm$  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<sup>-3</sup>; its mean value was 0.54  $\pm$  0.12 kg m<sup>-3</sup> (Table 1).

<sup>310 3.1.</sup> Characteristics of hydromulch roots

Table 1 - Main statistics of root characteristics in samples (n = 20) of hydromulched

320 hillslopes (Guilan province, Northern Iran).

Doot abaractoristics	Moon	Minimum	Maximum	Standard
Root characteristics	Wiean	IVIIIIIIIIIIIIIII		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

322

323

324 3.2. Variations of rill detachment capacity between soil conditions

325

The rill detachment capacity in DH soils was significantly (p < 0.05) lower compared to the DB plot. As shown in Figure 3, D<sub>c</sub> was on the average 0.027 kg m<sup>-2</sup> s<sup>-1</sup> in DH plots, a 1.5-fold value compared the DB soils (0.047 kg m<sup>-2</sup> s<sup>-1</sup>). Also, the variability of D<sub>c</sub> was lower in DH soils, as shown by the lower standard deviation (0.013 kg m<sup>-2</sup> s<sup>-1</sup> vs. 0.024 kg m<sup>-2</sup> s<sup>-1</sup> 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</li>
(DH), and deforested and bare (DB) plots.

339 3.2. Analysis of the relationships between rill detachment capacity and root
340 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).

350

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

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

352

353

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

356

The regression analysis applied to  $D_c$  and  $\tau$  using equation (2) showed that the slope (K<sub>r</sub>) and intercept ( $\tau_c$ ) of the interpolating lines were different between DH and DB soils. The coefficient of determination (R<sup>2</sup>) 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<sub>r</sub> was higher in DB soil (0.0078 s m<sup>-1</sup>) compared to DH plot (0.043 s m<sup>-1</sup>), while  $\tau_c$  was higher in DH soils (4.11 Pa) and lower in DB plots (3.91 Pa) (Figure 4).



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

- 371 4. Discussions
- 372

#### 373 4.1. Influence of hydromulching on rill detachment capacity

374

375 In this study, the deforested soils subjected to hydromulching or left bare had the same 376 characteristics (such as the soil type and texture) and experienced the same water 377 discharges and bed slopes in the experiments. Therefore, the effects of hydromulching 378 and, especially, the root characteristics can explain alone the changes in rill detachment 379 capacity and erodibility between the treatment and the control plots. Previous studies 380 have demonstrated that the conservation techniques based on hydromulching are able to 381 significantly reduce soil loss in several environmental conditions (e.g., Hubbert et al. 382 2012; Prats et al. 2013; Parsakhoo et al. 2018a; Ricks et al. 2020). The results of the 383 experiments carried out in the current investigation are in accordance to these studies. 384 As a matter of fact, hydromulching reduced on the average rill detachment capacity by 385 44% compared to the bare soil, with a peak of 54% for the minimum values of rill 386 detachment capacity. This reduction let us think that also soil loss, although not directly 387 measured in these experiments, can be lower in hydromulched soils compared to bare 388 soil. This reduction may be expected, since Robichaud et al. (2000) reported that 389 hydromulching is able to control erosion in the short term, because its application 390 enhances a vegetation cover with a dense root system. Conversely, other studies have 391 demonstrated that the vegetal cover might be insignificant for the prevention and control 392 of rill erosion (De Baets et al. 2007; Wang et al. 2014a).

393 The correlation analysis helps to explain which characteristics of the hydromulch roots 394 play a greater influence on the observed reduction in rill detachment capacity. This 395 statistical technique has identified significant correlations between rill detachment 396 capacity on one side and weight density and diameter of roots on the other side. More 397 specifically, when root weight density decreases, rill detachment capacity increases. 398 Root weight density is an important indicator of the ability of plants at reducing soil 399 detachment (Yoshinorui et al. 2016; Parhizkar et al., 2021a). Conversely, in soils with 400 higher root diameter, rill detachment capacity is higher. Also other studies have found 401 positive correlations between some parameters related to soil resistance to concentrated

402 erosion and root characteristics (e.g., Li et al. 1992; Wang et al. 2015; Wang and Zhang403 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.

407 First, it is well known that soils with a prominent vegetation cover show higher root 408 weight density (Parhizkar et al. 2020c; in press). This parameter, identified by the 409 correlation analysis among the root characteristics that mostly influence rill detachment 410 capacity determines a beneficial effect, reducing soil detachability (Li et al. 2015) and 411 thus on soil's resistance to particle detachment. The direct association between rill 412 detachment capacity and root weight density is in accordance with findings of many 413 authors (e.g., Zhang et al. 2013; Li et al. 2015; Wang et al. 2015). These studies state 414 that increases in root weight density are effective in reducing the soil detachability. 415 Among the other studies reporting similar impacts of the plant roots in reducing soil 416 detachment (e.g., Li et al. 1991; Li 1995), and specifically in controlling rill erosion 417 (Gyssels et al. 2005), it is interesting to notice that Zhang et al. (2013) reported an 418 exponential decrease in soil detachment capacity with the increase in root weight 419 density. However, this law has not been confirmed in our study, which found a 420 coefficient of determination of only 0.20 in regressing rill detachment capacity with root 421 weight density (data not shown).

422 Second, the root diameter is the other characteristic of root hydromulch that mostly 423 influences rill detachment capacity in the hydromulched soil. Root diameter was lower 424 than one mm in all experiments, and this size was effective in reducing rill detachment 425 capacity compared to the bare soil without grass roots. This size is in accordance with 426 findings of many authors (e.g., De Baets et al. 2006, 2007; Loades et al. 2010; Leung et 427 al. 2015; Li et al. 2015), who reported that roots with diameter less than one mm are 428 effective in controlling concentrated flow and protecting soil from rill detachment, with 429 clear reduction in hillslope erodibility. Conversely, Khanal and Fox (2017) showed that 430 erosion rates at high shear stress decrease with increasing root diameter.

431 Unexpectedly, the influence of the other root characteristics, length and biomass, on rill 432 detachment capacity was not evidenced by this study. The scarce influence of root 433 length on soil erodibility may be justified by the fact that the detachment of soil 434 particles is a surface process, whereas grass roots mainly penetrate in the sub-surface 435 layer of soil rather than extending on its surface (Yoshinori et al. 2016). The absence of 436 biomass effects on soil detachability can be explained by the low time elapsed from the 437 hydromulch application to the experiment. Organic matter supplied by biomass needs 438 more time to degrade and play beneficial effects on soil structure, such as aggregation 439 properties (Lucas-Borja et al. 2018). The role of these factors can be instead expected in 440 other land uses different from deforested areas. For example, Parhizkar et al. (2020a) 441 reported that vegetation cover with the effects of its roots can help to reduce soil 442 detachment in forestland and woodland of Northern Iran.

- 443
- 444

## 445 *4.2. Influence of hydromulching on rill erodibility*

446

447 Literature studies have clearly demonstrated that rill detachment rate and erodibility 448 depend on plant root characteristics (Mamo and Bubenzer 2001a, 2001b; De Baets and 449 Poesen 2010; Gyssels et al. 2006). As shown for rill detachment capacity, this study has 450 demonstrated that grass roots are able to decrease rill erodibility in hydromulched soils. 451 For bare soil, rill erodibility was 1.8 times greater than the value of the hydromulched 452 plot, while the ratio of  $\tau_c$  measured in DB and DH soils was close to one. This result is 453 consistent with the studies by Mamo and Bubenzer (2001a; 2001b), who found that rill 454 erodibility decreases by an exponential law in soils with living plant root. Moreover, Li 455 et al. (1991) showed that the decrease in rill detachment capacity and erodibility of soil 456 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. 457

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.

463 It is interesting to note that the erodibility estimated for the hydromulched plot is lower 464 compared to the values measured in grasslands in a previous work (Parhizkar et al. 465 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.

469 The values of rill erodibility and critical shear stress suggested by the present study are 470 useful to help land managers to simulate the hydrological impacts of soil conservation 471 measures, such as hydromulch application in deforested areas, in order to reduce the 472 erosion risk. As a matter of fact, rill erodibility and critical shear stress are the most 473 important parameters reflecting the soil resistance to rill erosion (Nearing et al. 1989). 474 Therefore, accurate values for these parameters are essential to achieve reliable 475 predictions of erosion by applying physically-based erosion models (Wang et al. 2016), 476 such as the Water Erosion Prediction Project (WEPP) (Laflen et al. 1991).

477

### 478 **5.** Conclusions

479

480 This study has evaluated rill detachment capacity in hydromulched and untreated plots 481 through flume experiments on soils sampled in deforested hillslopes of Northern Iran. 482 Rill detachment capacity in the hydromulched soil was significantly lower compared to 483 the bare plot. D<sub>c</sub> was positively and negatively correlated with diameter and density of 484 hydromulch roots, respectively. Rill erodibility was noticeably lower (-81%) in the 485 hydromulched soil compared to the bare plot. These outcomes show the effectiveness of 486 hydromulch roots with lower diameter and higher weight density in reduceing rill 487 detachment capacity. Moreover, by regressing rill detachment capacity on shear stress 488 upon the measurements, rill erodibility and critical shear stress for deforested hillslopes 489 (treated with hydromulching or left bare) were given. These regression models and 490 values help hydrologists in applications of erosion models to reduce erosion rates in 491 deforested hillslopes.

```
493 Funding
```

- 494
- 495 Faculty of Agricultural Sciences, University of Guilan.
- 496
- 497 Acknowledgments

The authors thank the Faculty of Agricultural Sciences, University of Guilan for theirsupport and experimental assistance.

501

502 References
----------------

503

Abdallah, A.M., 2019. The effect of hydrogel particle size on water retention properties
and availability under water stress. International Soil and Water Conservation Research.
7: 275-285.

507 Abrahams, A.D., Parsons, A.J., Luk, S.H., 1985. Field measurement of the velocity of

508 overland flow using dye tracing. Earth Surf Process Landf. 11: 653–657.

509 Aksoy, H., Kavvas, M.L., 2005. A review of hillslope and watershed scale erosion and

510 sediment transport models. Catena 64: 247–271.

511 Albaladejo Montoro, J., Alvarez Rogel, J., Querejeta, J., Díaz, E., Castillo, V., 2000.

512 Three hydro-seeding revegetation techniques for soil erosion control on anthropic steep

513 slopes. Land Degrad Dev. 11(4): 315-25.

Babcock, D.L., McLaughlin, R.A., 2013. Erosion control effectiveness of straw,
hydromulch and polyacrylamide in a rainfall simulator. J Soil Water Conserv. 68(3):
221-227.

517 Bagnold, R.A., 1966. An approach to the sediment transport problem for general

518 physics In US Geological Survey Professional Paper 422-I; US Government Printing

519 Office: Washington, DC, USA.

520 Bahrami, A., Emadodin, I., Ranjbar Atashi, M., Bork, H.R., 2010. Land-use change and

521 soil degradation: A case study, North of Iran. Agric Biol J N Am. 4: 600–605.

522 Bautista, S., Robichaud, P.R., Bladé, C., 2009. Post-fire mulching In: Cerdá A,

523 Robichaud PR editors Fire effects on soils and restoration strategies Volume 5 New

524 Hampshire: Science Publishers pp 353-72.

525 Beiraghdar, M., Yazdanpoor, S., Naderi, D., Zakerin, A., 2014. The effects of various

526 salicylic acid treatments on morphological and physiological features of zoysia grass

527 (Zoysia species). Journal of Novel Applied Sciences. 3(9): 984-987.

528 Bradshaw, C.J.A., Sodhi, N.S., Peh, K.S.H., Brook, B.W., 2007. Global evidence that deforestation amplifies

529 flood risk and severity in the developing world. Global Change Biology. 13(11): 2379-2395. Bryan, R.B.,

- Rockwell, D.L., 1998. Water table control on rill initiation and implications for
  erosional response. Geomorphology 23, 151–169. Chaplot, V., 2013. Impact of terrain
  attributes, parent material and soil types on gully erosion. Geomorphology, 186, 1–11.
- 533 Cherubin, M.R., Tormena, C.A., Karlen, D.L., 2017. Soil Quality Evaluation Using the
- 534 Soil Management Assessment Framework (SMAF) in Brazilian Oxisols with
- 535 Contrasting Texture. Rev Bras Ciência Solo. 41: 1806–9657.
- 536 De Baets, S., Poesen, J., 2010. Empirical models for predicting the erosion reducing
- 537 effects of plant roots during concentrated flow erosion. Geomorphology. 118: 425-432.
- 538 De Baets, S., Poesen, J., Gyssels, G., Knapen, A., 2006. Effects of grass roots on the 539 erodibility of topsoils during concentrated flow. Geomorphology. 76: 54–67.
- 540 De Baets, S., Poesen, J., Knapen, A., Galindo, P., 2007. Impact of root architecture on
- 541 the 23 erosion-reducing potential of roots during concentrated flow. Earth Surf Process

542 Landf. 32: 1323–1345.

- de Lima, J.L.M.P., Santos, L., Mujtaba, B., de Lima, M.I.P., 2019. Laboratory
  assessment of the influence of rice straw mulch size on soil loss. Adv Geosci. 48: 11–
  18.
- 546 Decaëns, T., Martins, M.B., Feijoo, A., Oszwald, J., Dolédec, S., Mathieu, J., Arnaud de
- 547 Sartre, X., Bonilla, D., Brown, G.G., Cuellar Criollo, Y.A., Dubs, F., Furtado, I.S.,
- 548 Gond, V., Gordillo, E., Le Clec'h, S., Marichal, R., Mitja, D., de Souza, I.M., Praxedes,
- 549 C., Rougerie, R., Ruiz, D.H., Otero, J.T., Sanabria, C., Velasquez, A., Zararte, L.E.M.,
- 550 Lavelle, P., 2018. Biodiversity loss along a gradient of deforestation in Amazonian
- agricultural landscapes. Conservation Biology. 32: 1380-1391. doi:101111/cobi13206.
- 552 Dodson, E.K., Peterson, D., 2009. Seeding and fertilization effects on plant cover and
- 553 community recovery following wildfire in the Eastern Cascade Mountains, USA. For
- 554 Ecol Manage. 258:1586-93.
- 555 Dube, H.B., Mutema, M., Muchaonyerwa, P., Poesen, J., Chaplot, V. A. 2020. global
- analysis of the morphology of linear erosion features. Catena, 190, 104542.

- 557 Eck, B., Barrett, M., McFarland, A., Hauck, L., 2010. Hydologic and Water Quality
- Aspects of Using a Compost/Mulch Blend for Erosion Control. J Irrig Drain Eng. 136:646–655.
- 560 Emadodin, I., 2008. Human-induced soil degradation in Iran in Ecosystem Services
- 561 Workshop; Salzau Castle: Kiel, Germany.
- 562 Ettbeb, A.E., Rahman, Z.A., Idris, W.M.R., Adam, J., Rahim, S.A., Tarmidzi, S.N.A.,
- 563 Lihan, T., 2020. Root tensile resistance of selected pennisetum species and shear
- strength of root-permeated soil. Applied and Environmental Soil Science. 6: 1-9.
- 565 Food and Agriculture Organization of the United Nations, 2000. Manual on Integrated
- 566 Soil Management and Conservation Practices (FAO Land and Water Bulletin); Food
- and Agriculture Organization of the United Nations: Rome, Italy.
- Foster, G.R., 1982. Modeling the erosion process. In Hydrologic Modeling of Small
  Watersheds; Haan, C.T., Ed.; ASAE: St. Joseph, MI, USA, pp. 296–380.
- 570 Fox, J.L., Bhattarai, S.P., Gyasi-Agyei, Y., 2010. Evaluation of different seed mixtures
- for grass establishment to mitigate soil erosion on steep slopes of railway batters.
  Journal of Irrigation and Drainage Engineering. 137: 624–631.
- 573 Geng, R., Zhang, G.H., Ma, Q.H., Wang, L.J., 2017. Soil resistance to runoff on steep 574 croplands in Eastern China. Catena. 152: 18–28.
- Gholoubi, A., Emami, H., Alizadeh, A., Azadi, R., 2019. Long term effects of
  deforestation on soil attributes: case study, Northern Iran Caspian. J Environ Sci. 17:
  73-81.
- 578 Govers, G., Everaert, W., Poesen, J., Rauws, G., De Ploey, J., Lautridou, J.P., 1990. A
- 579 long flume study of the dynamic factors affecting the resistance of a loamy soil to 580 concentrated flow erosion. Earth Surf Process Landf. 15: 313–328.
- 581 Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance
  582 of soils to erosion by water: A review. Prog Phys Geogr. 29: 189–217.
- 583 Gyssels, G., Poesen, J., Liu, G., Van Dessel, W., Knapen, A., De Baets, S., 2006.
- 584 Effects of cereal roots on detachment rates of single and double drilled top soils 585 during concentrated flow European. Journal of Soil Science. 57(3): 381-391.
- 586 Holt, G., Buser, M., Harmel, D., Potter, K., 2005. Comparison of cotton based hydro-
- 587 mulches and conventional wood and paper hydro-mulches-study II. J Cotton Sci. 9(3):
- 588 128–134.

- Hubbert, K.R., Wohlgemuth, P.M., Beyers, J.L., 2012. Effects of hydromulch on postfire erosion and plant recovery in chaparral shrublands of southern California.
  International Journal of Wildland Fire. 21: 155-167.
- 592 IRIMO (Islamic Republic of Iran Meteorological Organization), 2016. Annual Rainfall
- 593 Report. Available online: www.irimo.ir (accessed on 20 September 2019).
- Jiang, F., He, K., Huang, M., Zhang, L., Lin, G., Zhan, Z., Li, H., Lin, I., Håkansson, J.,
- 595 Ge, H., Huang, Y., 2020. Impacts of near soil surface factors on soil detachment process
- 596 in benggang alluvial fans. Journal of Hydrology. 590: 125274.
- 597 Govers, G., Giménez, R., & Van Oost, K. 2007. Rill erosion: exploring the relationship
- between experiments, modelling and field observations. Earth-Science Reviews, 84(3-4),87-102.
- 600 Kelarestaghi, A.A., Ahmadi, H., Jafari, M., 2006. Land use changes detection and
- 601 spatial distribution using digital and satellite data, case study: Farim drainage basin,
- 602 Northern of Iran. Desert. 11(2): 33-47.
- Khanal, A., Fox, G.A., 2017. Detachment characteristics of root-permeated soils from
  laboratory jet erosion tests. Ecological Engineering. 100: 335-343.
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the
  Köppen-Geiger climate classification updated. Meteorol Z. 15: 259–263.
- Laflen, J.M., Lane, J.L., Foster, G.R., 1991. WEPP A New Generation of Erosion
  Prediction Technology. J Soil Water Cons. 1991: 46 (1), pp 34-38.
- 609 Leung, F.T.Y., Yan, W.M., Hau, B.C.H., Tham, L.G., 2015. Root systems of native
- shrubs and trees in Hong Kong and their effects on enhancing slope stability. Catena.125: 102–110.
- 612 Li, M., Hai, X., Hong, H., Shao, Y., Peng, D., Xu, W., Yang, Y., Zheng, Y., Xia, Z.,
- 613 2019. Modelling soil detachment by overland flow for the soil in the Tibet Plateau of 614 China. Sci Rep. 9: 8063, doi:101038/s41598-019-44586-5.
- 615 Li, X.H., Zhang, Z.Y., Yang, J., Zhang, G.H., Wang, B., 2011. Effects of Bahia grass
- 616 cover and mulch on runoff and sediment yield of sloping red soil in southern China.
- 617 Pedosphere. 21: 238–243.
- 618 Li, Y., 1995. Plant Roots and Soils Anti Scourability on the Chinese Loess Plateau (in
- 619 Chinese) Beijing, China: Science Press.

- Li, Y., Xu, X.Q., Zhu, X.M., 1992. Preliminary-study on mechanism of plant-roots to
  increase soil antiscouribility on the Loess Plateau. Sci China Ser B–Chem. 35: 1085–
  1092.
- 623 Li, Y., Zhu, X.M., Tian, J.Y., 1991. Benefits of vegetation roots to improve erodibility

624 in Loess Plateau (in Chinese). Science Bulletin. 36(12): 935-938.

- 625 Li, Z.W., Zhang, G.H., Geng, R., Wang, H., Zhang, X.C., 2015. Land use impacts on
- soil detachment capacity by overland flow in the Loess Plateau, China. Catena. 124: 9–
  17.
- Liu, J., Zhou, Z., Zhang, X.J., 2019. Impacts of sediment load and size on rill
  detachment under low flow discharges. Journal of Hydrology. 570: 719–725.
- Loades, K.W., Bengough, A.G., Bransby, M.F., Hallett, P.D., 2010. Planting density
  influence on fibrous root reinforcement of soils. Ecol Eng. 36: 276–284.
- 632 Lucas-Borja, M.E., Zema, D.A., Plaza-Álvarez, P.A., Zupanc, V., Baartman, J., Sagra,
- 633 J., de las Heras, J., 2019. Effects of different land uses (abandoned farmland, intensive
- agriculture and forestland) on soil hydrological properties in Southern Spain. Water. 11:503.
- Lucas-Borja, M.E., Delgado-Baquerizo, M., 20190. Plant diversity and soil
  stoichiometry regulates the changes in multifunctionality during pine temperate forest
  secondary succession. Science of the Total Environment. 134204.
- 639 Lucas-Borja, M.E., Plaza-Álvarez, P.A., González-Romero, J., Miralles, I., Sagra, J.,
- 640 Molina-Peña, E., Moya, D., De las Heras, J., Fernández, C., 2020. Post-wildfire straw
- 641 mulching and salvage logging affects initial pine seedling density and growth in two
- 642 Mediterranean contrasting climatic areas in Spain. Forest Ecology and Management. in
- 643 press.
- 644 Lucas-Borja, M.E., Hedo, J., Yang, Y., Shen, Y., Candel-Pérez, D., 2018. Nutrient,
- 645 metal contents and microbiological properties of litter and soil along a tree age gradient
- 646 in Mediterranean forest ecosystems. Science of the Total Environment. 650: 749-758.
- 647 Mamo, M., Bubenzer, G.D., 2001a. Detachment rate, soil erodibility, and soil strength
- 648 as influenced by living plant roots part I: Laboratory study. American Society of
- 649 Agricultural Engineers. 44(5): 1167-1174.

- Mamo, M., Bubenzer, G.D., 2001b. Detachment rate soil erodibility and soil strength
  has influenced by living plant roots, Part II: Field study. Transactions of the American
  Society of Agricultural Engineers. 44(5): 1175–1181.
- 653 Marques, M.J., Bienes, R., Jiménez, L., Pérez-Rodríguez, R., 2007. Effect of vegetal
- 654 cover on runoff and soil erosion under light intensity events Rainfall simulation over
- 655 USLE plots. Science of the Total Environment. 378: 161–165.
- 656 McCullough, S.A., Endress, B.A., 2012. Do postfire mulching treatments affect plant
- 657 community recovery in California coastal sage scrub lands? Environ Manag. 49: 142–658 150.
- 659 McLauglin, R.A., Brown, T.T., 2006. Evaluation of erosion control products with and
- 660 without added polyacrylamide. J Am Water Resour Assoc. 42: 675–684.
- 661 Nearing, M.A., Foster, G.R., Lane, L.J., Finkner, S.C., 1989. A process based soil
- 662 erosion model for USDA Water Erosion Prediction Project technology. Trans ASAE.
- 663
   32: 1587-1593.
- 664 Nearing, M.A., Norton, L.D., Bulgakov, D.A., Larionov, G.A., West, L.T., Dontsova,
- 665 K.M., 1997. Hydraulics and erosion in eroding rills. Water Resour Res. 33: 865–876.
- 666 Owoputi, L., Stolte, W., 1995. Soil detachment in the physically based soil erosion
  667 process: a review. Trans ASAE. 38 (4): 1099–1110.
- 668 Parhizkar, M., Shabanpour, M., Khaledian, M., Cerdà, A., Rose, C.W., Asadi, H.,
- 669 Lucas-Borja, M.E., Zema, D.A., 2020. Assessing and Modeling Soil Detachment
- 670 Capacity by Overland Flow in Forest and Woodland of Northern Iran. Forests. 11(1):671 65.
- 672 Parhizkar, M., Shabanpour, M., Lucas-Borja, M.E., Zema, D.A., Li, S., Tanaka, N.,
- 673 Cerdà, A., 2020b. Effects of length and application rate of rice straw mulch on surface
- 674 runoff and soil loss under laboratory simulated rainfall. International Journal of
- 675 Sediment Research, In Press.
- Parhizkar, M., Shabanpour, M., Zema, D.A., Lucas-Borja, M.E., 2020c. Rill erosion and
  soil quality in forest and deforested ecosystems with different morphological
  characteristics. Resources. 9: 129. doi: 10.3390/resources9110129.
- 679 Parhizkar, M., Shabanpour, M., Miralles, I., Cerdà, A., Tanaka, N., Asadi, H., Lucas-
- 680 Borja, M.E., Zema, D.A., 2021. Evaluating the effects of forest tree species on rill
- 681 detachment capacity in a semi-arid environment. Ecological Engineering, 106158.

- Parsakhoo, A., Jajouzadeh, M., Rezaee Motlagh, A., 2018a. Effect of Hydromulch
  Binders on Reduction of Embankment-Induced Soil Erosion and Sediment
  Concentration. ECOPERSIA. 6(3):179-186.
- 685 Parsakhoo, A., Jajouzadeh, M., Rezaee Motlagh, A., 2018b. Effect of hydroseeding on
- 686 grass yield and water use efficiency on forest road artificial soil slopes. Journal of forest
- 687 science. 64(4): 157–163.
- 688 Patil Shirish, S., Kelkar Tushar, S., Bhalerao Satish, A., 2013. Mulching: A Soil and
- 689 Water Conservation Practice Research. Journal of Agriculture and Forestry Sciences. 1:690 26–29.
- 691 Prats, S.A., Abrantes, J.R., Crema, I.P., Keizer, J.J., de Lima, J.L.M.P., 2017. Runoff
- and soil erosion mitigation with sieved forest residue mulch strips under controlledlaboratory conditions. Forest Ecol Manag. 396: 102–112.
- 694 Prats, S.A., Malvar, M.C., Vieira, D.C.S., MacDonald, L., Keizer, J.J., 2013.
  695 Effectiveness of hydromulching to reduce runoff and erosion in a recently burnt pine
- 696 plantation in central Portugal. Land Degrad Dev. 27: 1319–1333.
- 697 Prosdocimi, M., Tarolli, P., Cerdà, A., 2016. Mulching practices for reducing soil water
  698 erosion: A review. Earth-Science Reviews. 161: 191-203.
- Ricks, M.D., Wilson, W.T., Zech, W.C., Fang, X., Donald, W.N., 2020. Evaluation of
  hydromulches as an erosion control measure using intermediate-scale
  experiments. Water. 12(2): 515.
- 702 Rivera, D., Mejías, V., Jáuregui, B.M., Costa-Tenorio, M, López-Archilla, A.I., Peco,
- B., 2014. Spreading topsoil encourages ecological restoration on embankments: Soil
  fertility, microbial activity and vegetation cover. PLoS ONE. 9: e101413.
- Robichaud, P.R., Beyers, J.L., Neary, D.G., 2000. Evaluating the effectiveness of
  postfire rehabilitation treatments. General Technical Report RMRS-GTR-63 USDA
  Forest Service, Rocky Mountain Research Station Fort Collins, Colorado.
- Rodgers, J.L., Nicewander, W.A., 1988. Thirteen ways to look at the correlation
  coefficient. Am Stat. 42: 59–66.
- 710 Scholl, B.N., Holt, G., Thornton, C., 2012. Screening study of select cotton-based
- 711 hydromulch blends produced using the Cross-Linked biofiber process. J Cotton Sci. 16:
- 712 249–254.

- 713 SDSD (Soil Science Division Staff), 2017. Soil Survey Manual, Ditzler, C., Scheffe, K.,
- 714 Monger, H.C., Eds, USDA Handbook 18 Government Printing Office: Washington, DC,
- 715 USA.
- 716 Shabanpour, M., Daneshyar, M., Parhizkar, M., Lucas-Borja, M.E., Zema, D.A., 2020.
- 717 Influence of crops on soil properties in agricultural lands of northern Iran. Sci Total
- 718 Environ. 134694.
- 719 Sheldon, J.C., Bradshaw, A.D., 1997. The development of a hydraulic seeding
- technique for unstable sand slopes I Effects of fertilizers, mulches and stabilizers. J
  Appl Ecol. 14(3): 905-18.
- Shen, N., Wang, Z., Zhang, Q., Chen, H., Wu, B., 2019. Modelling soil detachment
- capacity by rill flow with hydraulic variables on a simulated steep loessial hillslope.
  Hydrology Research 50 (1): 85–98.
- Shoemaker, A.L., 2009. Evaluation of anionic polyacrylamide as an erosion control
  measure using intermediate- scale experimental procedures MS Thesis, Auburn
  University, Auburn, AL.
- Singh Sidhu, R., 2015. Effectiveness of selected erosion control covers during
  vegetation establishment under simulated rainfall by MS Thesis, Auburn University,
  Auburn, AL.
- Soroush, F., Mousavi, F., Razmjoo, K.H., Mostafazadeh-Fard, B., 2008. Effect of
  treated wastewater on uptake of some elements by Turf grass in different soil textures.
- 733 Journal of Water and Soil. Agricultural Sciences and Technology. 22(2): 285-294.
- 734 Tyner, J.S., Yoder, D.C., Chomicki, B.J., Tyagi, A., .2011. A Review of Construction
- 735 Site Best Management Practices for Erosion Control Trans. ASABE. 54: 441–450.
- Wang, B., Zhang, G.H., Shi, Y.Y., Li, Z., 2015. Effects of Near Soil Surface
  Characteristics on the Soil Detachment Process in a Chronological Series of Vegetation
  Restoration. Soil Science Society of America Journal. 79(4): 1213-1222.
- 739 Wang, B., Zhang, G.H., Shi, Y.Y., Zhang, X.C., 2014b. Soil detachment by overland
- flow under different vegetation restoration models in the Loess Plateau of China. Catena.116: 51–59.
- 742 Wang, B., Zhang, G.H., Yang, Y.F., Li, F.F., Liu, J.X. 2018a. Response of soil
- 743 detachment capacity to plant root and soil properties in typical grasslands on the Loess
- 744 Plateau. Agric Ecosyst Environ 266: 68–75.

- 745 Wang, B., Zhang, G.H., Yang, Y.F., Li, P.P., Liu, J.X., 2018b. The effects of varied soil
- 746 properties induced by natural grassland succession on the process of soil detachment.
- 747 Catena. 166: 192–199.
- 748 Wang, B., Zhang, G.H., Zhang, X.C., Li, Z.W., Su, Z.L., Yi, T., Shi, Y.Y., 2014a.
- 749 Effects of near soil surface characteristics on soil detachment by overland flow in a

natural succession grassland. Soil Sci Soc Am J. 78: 589–597.

- 751 Wang, B., Zhang, G.H., 2017. Quantifying the binding and bonding effects of plant
- roots on soil detachment by overland flow in 10 typical grasslands on the Loess Plateau.
- 753 Soil Sci Soc Am J. 81: 1567–1576.
- Wang, D.D., Wang, Z.L., Shen, N., Chen, H., 2016. Modeling soil detachment capacity
- by rill flow using hydraulic parameters. J Hydrol. 535: 473–479.
- Yang, C.T., 1972. Unit stream power and sediment transport. J Hydrol Div ASCE. 98:
  1805–1826.
- Yoshinori, S., Sohei, O., Tetsuya, K., Kyoichi, O., Kazuki, N., 2016. Effects of plant
  roots on the soil erosion rate under simulated rainfall with high kinetic energy.
  Hydrological Sciences Journal. 61(13): 2435-2442.
- Zhang, G.H., Liu, B.Y., Liu, G.B., He, X.W., Nearing, M.A., 2003. Detachment of
  undisturbed soil by shallow flow. Soil Sci Soc Am J. 67: 713–719.
- Zhang, G. H., Liu, B. Y., Nearing, M.A., Huang, C.H., Zhang. K.L. 2002. Soil
  detachment by shallow flow. Trans. ASAE. 45(2): 351-357.
- 765 Zhang, G.H., Tang, K.M., Ren, Z.P., Zhang, X.C., 2013. Impact of grass root mass
- density on soil detachment capacity by concentrated flow on steep slopes. TransASABE. 56: 927–934
- 768 Zhang, G.H., Tang, K.M., Zhang, X.C., 2009. Temporal variation in soil detachment
- under different land uses in the Loess Plateau of China. Earth Surf Process Landf. 34:1302–1309.
- 771 Zhang, G.H., Liu, G.B., Tang, KM., Zhang, X.C., 2008. Flow detachment of soils under
- different land uses in the Loess Plateau of China. Trans ASABE. 51: 883–890.
- 773 Zhou, Z., and Zhang, X. J. 2019. Impacts of sediment load and size on rill detachment
- under low flow discharges. Journal of Hydrology, 570, 719-725.
- 775

# 776 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).

	Slope (S, %)	Water Water		Hydraulic	Shear	
Experiment		discharge	depth	radius	stress	
		$(q, L m^{-1} s^{-1})$	(h, cm)	(R, m)	<b>(τ, Pa)</b>	
1	10	0.22	0.610	0.006	5.633	
2		0.33	0.720	0.007	6.580	
3		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	15	0.22	0.514	0.005	7.150	
7		0.33	0.628	0.006	8.670	
8		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	20	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	25	0.33	0.434	0.004	10.155	
18		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	