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Evaluating the effects of forest tree species on rill detachment capacity in a semi-arid environment

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16 17 18	Evaluating the effects of forest tree species on rill detachment capacity in a semi-arid environment
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36	
37	Abstract
38	
39	The beneficial effects of plant roots in decreasing soil detachment in forest ecosystems
40	exposed to rill erosion are well known. However, these effects vary largely between
41	different plant species. There has been lots of research into the relationship between root-
42	soil systems and rill erodibility with a particular focus on grass species. Conversely, fewer
43	studies are available for tree species, especially in forests of semi-arid or arid environments.
44	Greater knowledge is therefore needed to identify the most effective tree species against rill
45	erosion in these ecosystems, where water availability is the limiting factor for vegetation
46	growth and afforestation is often the only solution to control erosion. To fill this gap, this
47	study evaluates the rill detachment capacity of soils with four tree species (Parrotia
48	persica, Carpinus betulus, Quercus castaneifolia, and Pinus taeda) in a semi-arid forest
49	ecosystem in Northern Iran. These species are typical of these forests, but they also grow in
50	other environmental contexts. The rill detachment was simulated in a laboratory flume at

five slope gradients (1% to 5%) and five flow rates (0.22 to 0.69 L $m^{-1} s^{-1}$) on soil samples 51 52 with each of the tree species. The specific goal of the study was to evaluate which tree 53 species with its specific root characteristics is most effective at reducing the rill detachment 54 capacity. Moreover, simple prediction models are proposed to evaluate if it is possible to 55 estimate the rill detachment capacity and rill erodibility (Kr) from the unit stream power for 56 the investigated tree species. The soils with Parrotia persica and Carpinus betulus showed 57 the lowest and the highest rill detachment capacity, respectively. The higher root system 58 biomass of *Parrotia persica* could have played a binding effect on the soil, thus improving 59 its aggregate stability thanks to the action of plant's root system. Based on these results, 60 Parrotia persica is able to provide a higher soil protection capacity against erosion 61 compared to the other tree species. A logarithmic function was accurate in predicting the rill detachment capacity from the unit stream power at water flow rates over 0.0025 m s⁻¹. 62 63 By a regression between the rill detachment capacity and the shear stress of the soil, rill 64 erodibility and critical shear stress of soils were estimated for the four tree species; the rill 65 erodibility and critical shear stress are important input parameters for physically-based 66 erosion models. Overall, the results of this study can support land planners in the choice of 67 tree species most indicated for soil conservation as well as in the extensive application of 68 erosion prediction models.

69

Keywords: forest; *Parrotia persica*; rill erodibility; unit stream power; root density;
shallow flow; soil erosion.

72

73 **1. Introduction**

74

75 Soil erosion is a complex environmental process, consisting of detachment from place, 76 transport, and deposition of soil particles, often at a long distance (Ellison, 1947; 77 Prosdocimi et al., 2016). Soil detachment is due to rainsplash and overland flow (Govers et 78 al., 1990), which are the main soil detachment mechanisms in inter-rill and rill erosion, 79 respectively (Zhang et al., 2003). Regarding rill erosion, its maximum value at zero 80 sediment concentration is called "soil detachment capacity" (Foster, 1982). This is the most 81 important parameter drivingsoil resistance to water erosion, particularly on steep slopes 82 (Wang et al., 2018b; Owoputi and Stolte, 1995). Regarding concentrated flow erosion, this 83 process is driven by "soil detachment capacity by rill flow" or, more simply, "rill 84 detachment capacity" (hereinafter indicated by "D_c"). Therefore, it is essential to quantify

which factors influence soil detachment capacity, in order to control and limit erosion by
appropriate soil management practices. In general, these practices are based on increasing
vegetal cover and/or modifying soil properties (Cerdà et al., 2016).

88 For technical, economic or legal reasons, it is not always easy to modify soil properties. 89 The use of vegetation with tree or herbaceous species is a more viable solution to control 90 surface erosion on hillslopes, reducing the soil erodibility. Revegetation for erosion control 91 is based on the effects of the above-ground biomass; the latter, however, can temporally 92 disappear, because of fire, overgrazing or concentrated erosion, particularly in arid and 93 semi-arid areas (De Baets et al., 2007). In these environments, the importance of below-94 ground biomass that can effectively control soil erosion rates is often neglected. The 95 beneficial effects of an extensive vegetal cover against soil erosion are many: the reduction 96 of surface runoff volume and velocity (Fiener and Auerswald, 2003; Koskiaho, 2003; Li et 97 al., 2013), the increase in water infiltration (De Baets et al., 2008; Li et al., 1992; 1995), 98 and bonding of soil particles at the soil surface (De Baets et al., 2006; 2007). Most of these 99 effects are due to the plant root system and are essential, particularly on steep slopes and 100 with loose soils, since plant roots reduce the sediment detachment by increasing the shear 101 strength of the root-soil matrix (Abdi et al., 2010; Herbrich et al., 2018; Wang et al., 102 2018a). However, these effects vary largely depending on the different characteristics of the 103 vegetation (tree, shrub or, grass layer; plant species; environmental conditions) (Jiao et al., 2008), and particularly on the size, distribution and density of the plant roots (De Baets et 104 105 al., 2007b; Gyssels et al., 2005). Based on the characteristics of the root system, the most 106 suitable plant species for erosion control can be properly selected to achieve a reduction in 107 soil erosion (Pollen, 2007). Among the root system characteristics, the root system biomass 108 (that is, the dry mass of roots in the soil) has been used by many authors as a key driver in 109 reducing soil detachment (Wang et al., 2014b; Li et al., 2015; Wang et al., 2018a; 2018b; 110 Parhizkar et al., 2020b). For example, Wang et al. (2014a; 2014b) found that root density is 111 the most influential factor on soil detachment capacity because of its physical and chemical 112 binding effects (De Baets et al., 2006; Zhang et al., 2013). De Baets et al. (2007) showed 113 that root density is correlated to soil detachment rate by a negative exponential equation. 114 Unfortunately, information on the effects of plant roots on topsoil resistance to rill erosion 115 is not sufficient (De Baets et al., 2007). A large variety of tree species exist, and each 116 species has its own specific root system characteristics. Previous studies have demonstrated 117 that different tree species exert different influences on the physico-chemical properties of 118 soils (e.g., Gyssels et al., 2005; Meek et al., 1992; Keller and Håkansson, 2010; Gyssels

and Poesen, 2003; Shabanpour et al., 2020), but particularly on soil detachment capacity
(Wang et al, 2014a; Zhang et al, 2013; Mamo and Bubenzer, 2001a; 2001b).

121 The studies that have evaluated the effects of plant root systems on soil erodibility and rill 122 detachment capacity have been carried out in specific environments (e.g., Loess Plateau in 123 China, Wang et al., 2014b; 2018a) and at the landscape scale (e.g., Li et al., 2015; Geng et 124 al., 2021, again in Loess Plateau) or have mainly focused on shrub and grass species (e.g., 125 De Baets et al., 2006; Zhang et al., 2013; Wang et al., 2021). In general, all these studies 126 have highlighted that the detachment rate of rooted soils is reduced compared to other 127 soils, with consequent increased soil stability (e.g., Mamo and Bubenzer 2001a; 2001b), 128 since erodibility is greatly reduced (even by more than 80-90%) compared to bare or 129 deforested soils (Wang et al., 2014a; Parhizkar et al., 2020b).

130 Some authors have also demonstrated that the effects of plant roots on soil erosion vary 131 depending on the plant species (Wang et al., 2018b) and the hydraulic parameters of the 132 water flow and soil properties (Gyssels et al., 2005). Despite this large body of literature, 133 less attention has been paid to tree species and, especially, to forest ecosystems, which, in 134 some environmental contexts (steep slopes and arid or semi-arid climate) may be 135 particularly prone to rill erosion. In fact, rill erosion is the most important erosive process on hillslopes with a high gradient (Wang et al., 2014b; Owoputi et al., 1995), and semi-arid 136 137 and arid climates - such as the Mediterranean Basin - are characterized by heavy 138 rainstorms, resulting in highly concentrated runoff rates with high erosion power (Fortugno 139 et al., 2017). Forest cover with trees that have a well-developed root system is highly 140 effective at reducing soil erosion (Gyssels et al., 2005; Parhizkar et al., 2020b). Moreover, 141 afforestation with tree species is often the only solution for reducing soil erosion in arid or 142 semi-arid ecosystems, where water availability is the limiting factor for vegetation growth 143 (Querejeta et al., 2001). Therefore, more research is needed to understand how a given 144 forest tree species with a root system having specific biomass characteristics drives the soil 145 detachment process. In other words, there is a need to evaluate the soil detachment capacity 146 under an individual plant species and different soil and hydraulic conditions. Such 147 evaluations are useful to select the most effective tree species for afforestation in steep 148 hillslopes with high erosion rates (Norris et al., 2008; Perez et al., 2017).

To fill these gaps, this study quantifies the rill detachment capacity in soils sampled under four species of adult trees (*Parrotia persica, Quercus castaneifolia, Pinus taeda* and *Carpinus betulum*) in Saravan Forest Park (Northern Iran), using an experimental flume. Moreover, simple models are proposed for the specific environmental conditions and tree 153 species, to predict the soil detachment capacity and rill erodibility. This investigation adds 154 the effect of the plant components to the results of a previous study by Parhizkar et al. 155 (2020a), carried out at the landscape scale under the same experimental conditions. These 156 authors showed that: (i) the soil detachment capacity of concentrated flow is lower in 157 forests and woodlands compared to grasslands and croplands; (ii) the unit stream power of 158 water flow is a very accurate predictor of soil detachment capacity. Following this 159 approach, our research questions were the following: (i) Which tree species with its specific 160 root system is more able to reduce the rill detachment capacity?; (ii) Are the prediction models proposed by Parhizkar et al. (2020a) also valid at a smaller scale for the analyzed 161 162 tree species?

163

164 **2. Materials and methods**

165

166 2.1. Study area

167

The province of Guilan (Northern Iran) lies between the southern coast of the Caspian Sea and the northern part of the Alborz Mountains. The landscape of this province consists of a green belt of old-growth Hyrcanian forests with high diversity of tree species and plant communities (Amoopour et al., 2016). According to Parhizkar et al. (2020a), special attention must be paid to the forests of this province, where existing problems of erosion may increase if soil conservation issues are neglected.

The experimental site is located in Saravan Forest Park, which is one of the oldest forests in
Guilan province (outlet coordinates 37°08'04" N, 49°39'44" E). The park drains the Saravan

176 watershed (coordinates $37^{\circ}08'04''$ N, $49^{\circ}39'44''$ E), which covers an area of 14.87 km² at an

177 elevation from 50 to 250 m (Figure 1).







(b)

179

180 Figure 1 - Geographical location (a) (source: Google Earth, 2020) and aerial map (b) in the

- 181 study area (Saravan Forest Park, Northern Iran).
- 182

183 This area has a Mediterranean climate, *Csa* type, according to the Köppen–Geiger 184 classification (Kottek et al., 2006). The mean annual precipitation and temperature are 1360 185 mm and 16.3 °C, respectively (IRIMO, 2016); precipitation is mainly concentrated in the

186 coldest months and scarce in the dry period (Figure 1(SD)).

187 The Saravan watershed features an abundant biodiversity of forest plants, including 80 tree

and shrub species (Sagheb-Talebi, et al., 2005; Hosseini, 2003, Kartoolinejad, et al., 2007).

189 The dominant tree species are Carpinus betulus L. (C. betulus), Quercus castaneifolia

190 C.A.Mey. (Q. castaneifolia), Pinus taeda L. (P. taeda), and Parrotia persica C.A.Mey. (P.

191 persica) (Picchio et al., 2020; Mirabolfathy et al., 2018; Payam and Pourrajabali, 2020;

192 Karimi et al., 2018). These species are typical of Northern Iran but grow throughout the

193 Southern Caspian area (*P. persica* and *Q. castaneifolia* are also well diffused in Turkey and

- 194 Azerbaijan), South-eastern United States (P. taeda), and Western Asia and Central,
- 195 Eeastern, and Southern Europe (C. betulus). Other shrub and herbaceous species in the area

are Artemisia annua L., Cynodon dactylon (L.) Pers., Hedera helix L., Hedera pastuchovii
Woron. Ex Grossh., Hypericum androsaemum L., Hypericum perforatum L., Juncus
bufonius L., Juncus glaucus Ehrh., Mentha pulegium L., Morus alba L., Primula
heterochoroma Starf., Prunus domestica L., Scutelaria albida L., and Solanum dulcamara
L.

201 Regarding the tree species, *P. persica* is a deciduous tree from Hamamelidaceae family, 202 specifically native tonorthern Iran (Sefidi et al., 2011; Karimi et al., 2018). This is a highly 203 ornamental tree or large shrub that can grow at an altitude of 20-25 m and tolerates drought, 204 heat, wind and cold (Gilman, 2014). C. betulus is a semi-shade tolerant species (Marvie-205 Mohadjer, 2019), while P. taeda is an exotic and fast growing coniferous species (Picchio 206 et al., 2020), which is used for commercial plantations. Q. castaneifolia is one of the most 207 important native oak species of Iran (Payam and Pourrajabali, 2020). Table 1 shows the 208 main physiological characteristics of these tree species surveyed in the study area.

209

210 Table 1 – Main physiological characteristics (mean \pm std. dev.) of the forest tree species

211 surveyed in the study area (Saravan Forest Park, Northern Iran).

212

Trac spacios	Height	Diameter ^(*)	Cover	
The species	(m)	(m)	(%)	
Parrotia persica	19 ± 0.6	0.57 ± 0.03	40	
Pinus taeda	16 ± 0.3	0.26 ± 0.03	30	
Carpinus betulus	22 ± 0.7	0.60 ± 0.04	15	
Quercus castaneifolia	23 ± 0.7	0.61 ± 0.04	15	

213 Note: (*) measured in this study at breast height.

214

215 Four mixed forests, with C. betulus, Q. castaneifolia, P. taeda and P. persica as prevalent 216 species in areas with the same slope gradient were selected for this study (Abedi and 217 Pourbabaei, 2011; Amoopour et al., 2016). On average, the C. betulus and Q. castaneifolia 218 species each cover 15% of the area, while P. persica and P. taeda are the dominant species 219 on 40% and 30% of the total area, respectively (Table 1). All the species are less than 15-20 220 years old. P. persica shows a fibrous root system growing horizontally in the soil (Abdi et 221 al., 2014). By contrast, *Q. castaneifolia*, *P. taeda*, and *C. betulus* have deep taproot 222 systems, and their roots grow vertically along the soil profile (Hacke et al., 2000; Rewald et 223 al., 2016; Abdi and Deljouei, 2019). C. betulus has the largest and deepest root system with the coarsest root diameter (Kooch et al., 2016; Bonyad, 2006). About ten years ago, some of the hillslopes in Saravan Park were deforested to install high-voltage electricity pylons, with high density tree and plant cover being totally removed (Parhizkar et al., 2020b). This deforestation induced intense rill erosion (Figure 2), meaning management action is absolutely necessary to avoid further biodiversity losses.

229



Figure 2 - Views of rill erosion on hillslopes with previous cover of *Quercus castaneifolia*after deforestation (Saravan Forest Park, Northern Iran) - (a, aerial view using a drone, and
b, front view).

235

236 2.2. Soil sampling procedure

237

238 To measure the rill detachment capacity of the soil (D_c) , between October and November 239 2019 undisturbed samples were collected in each of the areas with a dominant species 240 among P. persica, P. taeda, C. betulus, and Q. castaneifolia. Five samples were collected 241 around five trees for each species. For each tree, two quadrats (1 x 1 m and 2 x 2 m) were 242 overlaid on the ground. Two samples were collected in the vertices of the diagonal of the 243 first quadrat, and two others were collected in the vertices of the opposite diagonal of the 244 second quadrat. The fifth sample was collected immediately beside the trunk. This design 245 allowed sampling in different positions (two opposite diagonals) and three distances from 246 the tree (0, 0.7 and 1.4 m).

The sampling procedure, adapted to this study from the works of Zhang et al. (2003; 2008), is described in more detail in the paper by Parhizkar et al. (2020a). To summarise, the samples were extracted from the soil using a steel ring (diameter of 0.1 m and height of 0.05 m), after removing rocks, weeds, and litter from the soil surface. Then the soil cores in 251 the ring were transported to the laboratory, with the maximum care, to avoid soil 252 disturbance.

253

254 2.3. Soil analyses

255

An additional set of 100 soil samples (25 samples \times 4 tree species) was randomly collected in the same locations, to measure the root system biomass (RSB, by the washing method over a 1-mm sieve and subsequent oven drying at 65 °C), soil content of organic matter (OM, by the potassium dichromate colorimetric method), aggregate stability in water of soil (AS, De Leenheer and De Boodt, 1959), and bulk density (BD) (both using the wet-sieving and oven-drying methods).

262

263 2.4. Measurement of rill detachment capacity

264

A laboratory-scale flume with a rectangular cross section (length of 0.5 m and width of 0.2 m) was used to generate rill flow to evaluate the rill detachment capacity (D_c , [kg s⁻¹ m⁻²]) of soil samples for each tree species at different values of flow rate and soil slope. Each "experiment" was a combination of flow rate, slope gradient, and species simulated in the flume, of which a complete description is reported in Asadi et al. (2011), Raei et al. (2015), and Parhizkar et al. (2020a).

271 To summarise, each soil core was collected using a steel ring (Section 2.2) and inserted in a 272 hole of the flume bed, close to the downstream outlet, with the sample's upper surface 273 adjusted to the same level as that of the flume bed surface. Then the flow rate and flume 274 profile slope were adjusted to the desired values. Using clean water fed upstream of the 275 flume, D_c and the hydraulic parameters of the water flow (Section 2.6) were measured over 276 a 5-300 second period. The experimental test ended when the depth of the eroded soil in 277 the steel ring reached 0.015 m. After each test, the sample of wet soil was oven dried at 105 278 °C for 24 h to determine its dry weight.

After the start of each experiment in the flume, we expected that the flow would become steady. Then, using a level probe (accuracy of 1 mm), the water depth (h, [m]) was measured at three points (0.01 m from the right and left sides and in the middle for each of two cross sections, located at 0.4 m and 1 m from the flume outlet). Then the mean flow depth was calculated as the average value of these six measurements.

284 D_c was calculated as the average value of four replicates using equation (1):

285	
286	$D_c = \frac{\Delta M}{A \cdot \Delta t} \tag{1}$
287	
288	where:
289	- $\Delta M [kg] = dry$ weight of detached soil
290	- $\Delta t [s] =$ experiment duration [s]
291	- $A[m^2]$ = area of soil sample.
292	
293	2.5. Experimental design
294	
295	For each soil sample of the four plant species (C. betulus, Q. castaneifolia, P. taeda, and P.
296	<i>persica</i>), five water flow rates per unit width (q, 0.26, 0.35, 0.45, 0.56, and 0.67 L m ⁻¹ s ⁻¹)
297	and five slope gradients (S, 1%, 2%, 3%, 4%, and 5%) were simulated in the flume, and
298	each experiment consisted of four replicates. Overall, 400 soil samples (4 plant species \times 5
299	water flow rates \times 5 slope gradients \times 4 replications) were subjected to the experiments.
300	
301	2.6. Determination of the hydraulic parameters
302	
303	The values of q were measured five times per experiment (collecting the water into a
304	graduated plastic cylinder), while the water velocity (v , [m s ⁻¹]) was estimated using the

fluorescent dye technique in ten replicated measurements. Water viscosity was computed from the temperature. The mean velocity (V, [m s⁻¹]) was calculated reducing v by 0.6, 0.7, or 0.8, when the flow was laminar, transitional or turbulent, respectively (Abrahams et al., 1985).

309 In accordance with several authors (Nearing et al., 1997), *R*, *Re*, τ (Foster, 1982), Ω 310 (Bagnold, 1966), and ω (Yang et al., 1972) were calculated using the following equations:

311

$$312 \qquad R = \frac{h \cdot p}{2p + h} \tag{2}$$

313

$$314 \quad \tau = \rho g R S \tag{3}$$

$$316 \qquad \Omega = \rho g S q \tag{4}$$

317	
318	and
319	
320	$\omega = SV \tag{5}$
321	
322	where:
323	- $g = gravity acceleration [m s^{-2}]$
324	- $p = $ flume width [m]
325	- R = hydraulic radius [m]
326	- Re = Reynolds number [–]
327	- α = kinetic energy correction (in this case assumed as one)
328	- $\rho = \text{water density } [\text{kg m}^{-3}]$
329	- $\omega = \text{unit stream power [m s^{-1}]}$
330	- $\Omega = \text{stream power [kg s}^{-3}].$
331	
332	The values of the hydraulic parameters calculated for each flow rate and profile slope in the
333	experimental flume are reported in Table 2(SD) of the Supplementary Data.
334	
335	2.7. Modelling of rill detachment capacity and rill erodibility
336	
337	The measured values of D_c (considered as the dependent variable) were regressed on ω
338	(independent variable) using linear and non-linear equations (the latter with power or
339	logarithmic functions) for each tree species, to identify the most accurate predictive model.
340	The accuracy of these equations was checked using a set of statistics (mean, standard
341	deviation, minimum and maximum values), and summary and difference indexes: the
342	coefficient of determination (R ²), coefficient of efficiency (E), root mean square error
343	(RMSE), and coefficient of residual mass (CRM). The equations to calculate these indexes
344	with the acceptance limits are reported in Table 2 (Zema et al., 2012; Krause et al., 2005;
345	Moriasi et al., 2007; Van Liew and Garbrecht, 2003).
346	

347 Table 2 - Indexes and related equations, and range of variability to evaluate the prediction

- 348 capacity of the models.
- 349

Index	Equation	Range of	Acceptance limit and
Index	Equation	variability	notes
Coefficient of determination (R ²)	$\mathbf{r}^{2} = \left[\frac{\sum_{i=1}^{n} (O_{i} - \overline{O})(P_{i} - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O_{i} - \overline{O})^{2}} \sqrt{\sum_{i=1}^{n} (P_{i} - \overline{P})^{2}}}\right]^{2}$	0 to 1	 > 0.5 (Santhi et al., 2001; Van Liew et al., 2003; Vieira et al., 2018)
Coefficient of efficiency (E, Nash and Sutcliffe, 1970)	$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$	-∞ to 1	"Good" model accuracy if $E \ge 0.75$, "satisfactory" if $0.36 \le$ E < 0.75 and "unsatisfactory" if $E <$ 0.36 (Van Liew and Garbrecht, 2003)
Root mean square error (RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$	0 to ∞	< 0.5 of observed standard deviation (Singh et al., 2004)
Coefficient of residual mass (CRM or PBIAS, Loague and Green, 1991)	$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}$	$-\infty$ to ∞	 < 0.25 (Moriasi et al., 2007) - CRM < 0 indicates model underestimation - CRM > 0 indicates model overestimation (Gupta et al., 1999)

350 Notes: n = number of observations; O_i , P_i = observed and predicted values at the time step i; \overline{O} = mean of 351 observed values.

352

- Finally, the rill erodibility (K_r , [s m⁻¹]) was estimated as the slope and intercept of equation
- 354 (6) (Nearing et al., 1989):
- 355

$$356 \qquad D_C = K_r \left(\tau - \tau_c \right) \tag{6}$$

358	where:
359	- $\tau =$ hydraulic shear stress [Pa]
360	- $\tau_c = critical shear stress [Pa]$
361	
362	
363	2.8. Statistical analysis
364	
365	The statistical significance ($p < 0.05$) of the differences in the soil properties among the tree
366	species was evaluated using the t-test. The samples were assumed to be independent, and
367	their distribution was checked by QQ-plots.
368	Then, the analysis of covariance (ANCOVA) was applied to D_c (dependent variable), using
369	the tree species (categorical variable), and the slope and flow rate (numerical variables) as
370	factors. The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the
371	statistical significance of the differences in D_c among the tree species. To satisfy the
372	assumptions of the statistical tests (equality of variance and normal distribution of
373	samples), the data were subjected to a normality test or were square root-transformed
374	whenever necessary.
375	Finally, Pearson's matrix was calculated to find correlations among the soil properties. The
376	principal component analysis (PCA) was also applied to the soil properties to select a few
377	derivative parameters and to cluster soil samples in groups related to each tree species.
378	All statistical analyses were conducted by XLSTAT 9.0 software (Addinsoft, Paris,
379	France).
380	
381	3. Results
382	
383	3.1. Variability of soil properties and rill detachment capacity among the tree species
384	
385	The texture of the soil samples was silty clay loam (according to the USDA classification,
386	33% clay, 46% silt, and 19% sand), without significant variations among the tree species.
387	The differences in texture and bulk density (on average 1359 kg m ⁻³) of the soil samples
388	were not significant (Table 3). Conversely, the other soil properties were in general
389	significantly different among the tree species. More specifically, the aggregate stability was
390	higher (0.72 ± 0.05) in <i>P. persica</i> and lower (0.48 ± 0.06) in <i>C. betulus</i> The latter species
391	showed the lowest root system biomass $(0.51 \pm 0.03 \text{ kg m}^{-3})$, while the maximum value

392 $(0.87 \pm 0.02 \text{ kg m}^{-3})$ was recorded in *C. betulus* Organic matter was $1.63 \pm 0.01\%$ in *C. betulus*, $1.73 \pm 0.01\%$ in Q. castaneifolia, $1.96 \pm 0.01\%$ in *P. persica*, and 1.84 ± 0.02 in *P. taeda* The differences in OM content among the species were significant, except for *C. betulus* and *Q. castaneifolia* (Table 1).

396

Table 3 - Main properties (mean ± standard deviation) of forest soil sampled under four
tree species in Saravan Forest Park (Northern Iran).

399

		Tree species						
Soil property		C. betulus	Q. castaneifolia	P. persica	P. taeda			
	ClC	33.8 ± 0.33 a	33.7 ± 0.46 a	33.5 ± 0.24 a	33.5 ± 0.23 a			
<i>Texture (%)</i>	SiC	46.9 ± 0.61 a	46.8 ± 0.60 a	46.7 ± 0.35 a	46.9 ± 0.35 a			
	SaC	19.3 ± 0.47 a	19.5 ± 0.25 a	19.8 ± 0.25 a	19.6 ± 0.23 a			
$BD \ (kg \ m^{-3})$		1384 ± 12.29 a	1366 ± 10.50 a	1331 ± 13.99 a	1355 ± 11.73 a			
$RSB \ (kg \ m^{-3})$		0.51 ± 0.03 a	$0.62\pm0.02~b$	$0.87\pm0.02~\mathrm{c}$	$0.70\pm0.07~b$			
AS (-)		0.48 ± 0.06 a	0.55 ± 0.04 a	$0.72\pm0.05~b$	0.61 ± 0.06 c			
OM (%)		1.63 ± 0.01 a	1.73 ± 0.01 a	$1.96\pm0.01~b$	$1.84 \pm 0.02 \text{ c}$			

400 Notes: OM = organic matter content; BD = bulk density; RSB = root system biomass; AS = aggregate

401 stability; SaC = sand content; SiC = silt content; ClC = clay content; the letters indicate significant differences 402 among tree species at p < 0.05 of the *t*-test (n = 25 for each species).

403

404 D_c was significantly influenced by the tree species (p < 0.05). The mean value was the 405 highest for *C. betulus* (0.00336 kg m⁻² s⁻¹) and the lowest for *P. persica* (0.00226 kg m⁻² 406 s⁻¹). Therefore, the ratio between the maximum and minimum D_c was on average 1.49. Q. 407 castaneifolia and *P. taeda* had intermediate D_c (0.0031 and 0.0026 kg m⁻² s⁻¹, respectively) 408 between the extreme values. The variability of D_c is noticeable among the tree species, as 409 shown by coefficients of variation (ratio of standard deviation by mean) between 78.4% (*C.* 410 *betulus*) and 92.9% (*P. persica*) (Figure 3).

411





Different letters indicate significant differences after ANOVA at p < 0.05.



416 Figure 3 - Box-whisker plot of rill detachment capacity in forest soils sampled under four 417 tree species in Saravan Forest Park (Northern Iran) (n = 25 for each species).

418

419 Pearson's matrix shows that the correlations of D_c with the other soil properties were 420 generally low (coefficient of correlation R < 0.27) and significant only with the root system 421 biomass (R = -0.257) and aggregate stability (R = -0.261). Conversely, the correlations 422 between the other pairs of soil properties were high and significant. For instance, the 423 organic matter content was correlated with the root system biomass (R = 0.942), aggregate 424 stability (R = 0.837), and bulk density (R = -0.843). Moreover, the correlations among the 425 latter soil properties were also high (R = -0.789 between the bulk density and the root 426 system biomass, -0.686 between the bulk density and the aggregate stability, and 0.840 427 between the root system biomass and the aggregate stability). As regards the soil texture, only the silt content was significantly correlated with sand (R = -0.507) and clay (R = -428 429 0.470), although *R* was not high (Table 4).

430

431 Table 4 - Pearson's correlation matrix among the properties of forest soils sampled under 432 four tree species (n = 25 for each species) in Saravan Forest Park (Northern Iran).

Soil property	D_c	OM	BD	RSB	AS	SaC	SiC	ClC
D _c		-0.159	-0.045	-0.257	-0.261	-0.057	0.097	0.083

OM		-0.843	0.942	0.837	0.230	-0.289	-0.141
BD			-0.789	-0.686	-0.237	0.240	0.174
RSB				0.840	0.220	-0.243	-0.143
AS					0.135	-0.222	-0.079
SaC						-0.507	0.059
SiC							-0.470
ClC							

434

Notes: $D_c = rill$ detachment capacity; OM = organic matter content; BD = bulk density; RSB = root system 435 biomass; AS = aggregate stability; SaC = sand content; SiC = silt content; ClC = clay content; values in bold 436 are different from 0 at p level < 0.01.

437

438 PCA provided three principal components (PCs), which explained 48.7% (PC1), 24.7% 439 (PC_2) , and 13.0% (PC_3) of the total variance of the properties of the soils collected under 440 the four tree species. The first two PCs explained 73.3% of this variance. The properties 441 related to the soil texture had significant loadings on PC₂ (very high for clay, over 0.90). 442 The other soil properties significantly influenced the first PC with high loadings (over 443 0.75), while D_c heavily weighed on PC₃ (loading of 0.92) (Table 5). In other words, these 444 loadings confirm the results of Pearson's correlations (high r coefficients and therefore 445 strong associations among organic matter, bulk density, root system biomass, and aggregate 446 stability), but no direct association was found between D_c and the other soil properties 447 (Table 5 and Figure 4a).

- 448
- 449

450 Table 5 - Loadings of the original variables (properties of forest soils collected under four tree species) on the first two principal components (PC₁ and PC₂) (n = 25 for each species 451 452 in Saravan Forest Park, Northern Iran).

Soil	Principal components						
properties	PC_1	PC_2	PC_3				
D _c	0.053	0.000	0.921				
OM	0.928	0.010	0.003				
BD	0.754	0.002	0.091				
RSB	0.901	0.011	0.004				
AS	0.782	0.008	0.013				

SaC	0.342	0.332	0.005
SiC	0.050	0.945	0.000
ClC	0.083	0.665	0.005

454 Notes: $D_c = rill$ detachment capacity; OM = organic matter content; BD = bulk density; RSB = root system

biomass; AS = aggregate stability; SaC = sand content; SiC = silt content; ClC = clay content; values in bold

456 correspond for each variable to the factor for which the loading is the largest.

457

458 The plot of the sample scores on the first three PCs shows clear differences in soil properties among the

459 studied tree species. Four well-differentiated groups, one for each tree species, are 460 evidenced, with only a limited overlapping of groups for the *P. taeda* and Q. castaneifolia

461 species (Figure 4b).

462



465 Legend: D_c = rill detachment capacity; OM = organic matter content; BD = bulk density; RWD = root system
466 biomass; AS = aggregate stability; SaC = sand content; SiC = silt content; ClC = clay content: PC = principal
467 component.
468

- Figure 4 Loadings of soil parameters (a), and scores of forest soil samples (b) on the first
 two principal components (PC) for four tree species in Saravan Forest Park (Northern
 Iran). (The circle size is proportional to the values of the third PC.)
- 472
- 473 *3.2. Relationships among rill detachment capacity and unit stream power and estimation of*
- 474 *rill erodibility*
- 475
- 476 Figure 5 shows that at low values of the unit stream power ω (< 0.005–0.006 m s⁻¹) the
- 477 differences in D_c were small; moreover, these differences increased with ω .



Unit stream power (m s⁻¹)

478

Figure 5 - Correlations between the rill detachment capacity and unit stream power in forest soils sampled under four tree species in Saravan Forest Park (Northern Iran) (n = 25 for each species).

482

In the previous study by Parhizkar et al. (2020a), the best predictor of D_c in forests was ω , and the interpolating equation was a power function. In this investigation, when the two variables were regressed using power equations, the coefficients of determination were high ($R^2 > 0.85$), but the prediction capacity of these equations (different for each tree species) 487 was not always good, as shown by the values of E (> 0.75 only for *P. taeda*) (Tables 6 and 7). Adopting a linear equation, the values of R^2 and E increased for three of the four tree 488 species. Only one model (for *P. persica*) was not accurate (E = 0.43), due to the large 489 490 overestimation of D_c . The best model to predict D_c from ω was a logarithmic equation, for 491 which all the evaluation indexes were good and the statistics (e.g., mean and maximum 492 values) between predictions and observations were very close. However, in some cases 493 (that is, at very low ω) the model gives negative values of D_c , and this suggests application only in the case of $\omega > 0.0025$ m s⁻¹. This limitation is acceptable, because a low ω 494 characterizes water flow with limited erosive power. In general, all the equations 495 496 overestimated the observed D_c , as shown by the negative CRM, but the RMSE was always 497 satisfactory (except for the linear equation applied to P. persica) (Tables 6 and 7).

498

499 Table 6 - The equations correlating D_c (kg m⁻² s⁻¹) with the unit stream power (ω , m s⁻¹) in 500 forest soils sampled under four tree species in Saravan Forest Park (Northern Iran) (n = 25501 for each species).

Function	Tree species	Equation
	C. betulus	$D_c = 3.620 \ \omega^{1.559}$
Power	Q. castaneifolia	$D_c = 4.673 \ \omega^{1.640}$
1000	P. persica	$D_c = 17.744 \omega^{2.024}$
	P. taeda	$D_c = 5.434 \ \omega^{1.720}$
	C. betulus	$D_c = 0.3487 \ \omega + 0.0002$
Linear	Q. castaneifolia	$D_c = 0.3420 \ \omega + 0.0004$
	P. persica	$D_c = 0.3061 \ \omega + 0.0006$
	P. taeda	$D_c = 0.2820 \ \omega + 0.0006$
	C. betulus	$D_c = 0.0026 \ln \omega + 0.0163$
Logarithmic	Q. castaneifolia	$D_c = 0.0025 \ln \omega + 0.0156$
Linear P. ta Q. casta P. per P. per P. ta C. be Q. casta P. per P. ta C. be	P. persica	$D_c = 0.0020 \ln \omega + 0.1220$
	P. taeda	$D_c = 0.0022 \ln \omega + 0.0134$

Table 7 - Values of the criteria adopted for evaluating the accuracy of equations in Table 6 to predict the rill detachment capacity from the unit
 stream power in soils sampled under four tree species in Saravan Forest Park (Northern Iran).

Equation		Soil		Sta	atistic	Index					
structure	Tree species	detachment capacity	Mean	Minimum	Maximum	Standard deviation	\mathbb{R}^2	Е	CRM	RMSE	
	C. betulus	Observed	0.0034	0.0001	0.0077	0.0026	0.85	0.71	-0.03	0.001	
		Predicted	0.0035	0.0001	0.0119	0.0034					
Power	O castaneifolia	Observed	0.0031	0.0001	0.0074	0.0026	0.85	0.71	-0.03	0.001	
	Q. custancijotta	Predicted	0.0032	0.0000	0.0114	0.0032	0.05				
	P. persica	Observed	0.0023	0.0000	0.0058	0.0021	0.86	0.63	-0.11	0.001	
		Predicted	0.0025	0.0000	0.0106	0.0029	0.00				
	P taeda	Observed	0.0026	0.0000	0.0065	0.0023	0.90	0.82	-0.04	0.001	
	1. 000000	Predicted	0.0027	0.0000	0.0099	0.0028	0.90	0.02			
Linear	C. betulus	Observed	0.0034	0.0001	0.0077	0.0026	0.92	0.90	-0.12	0.001	
		Predicted	0.0038	0.0005	0.0091	0.0025	0.72	012 0			
	O castaneifolia	Observed	0.0031	0.0001	0.0074	0.0026	0.94	0.84	-0.26	0.001	
	g. castanetjona	Predicted	0.0039	0.0007	0.0091	0.0025	0.9	0.01	0.20	0.001	
	P. persica	Observed	0.0023	0.0000	0.0058	0.0021	0.95	0.43	-0.65	0.002	
	- · p • · ~ · •	Predicted	0.0037	0.0009	0.0084	0.0022	0.50	00		0.002	

	P. taeda	Observed	0.0026	0.0000	0.0065	0.0023	0.96	0.78	-0.36	0.001	
		Predicted	0.0035	0.0009	0.0078	0.0020		0170			
Logarithmic	C. betulus	Observed	0.0034	0.0001	0.0077	0.0026	0.87	0.86	-0.05	0.001	
		Predicted	0.0035	-0.0019	0.0068	0.0024					
	Q. castaneifolia	Observed	0.0031	0.0001	0.0074	0.0026	0.85	0.84	-0.07	0.001	
		Predicted	0.0033	-0.0019	0.0064	0.0023					
	P persica	Observed	0.0023	0.0000	0.0058	0.0021	0.80			0.001	
	1. perstea	Predicted	0.0024	-0.0018	0.0049	0.0019		0.00	0100		
	P taoda	Observed	0.0026	0.0000	0.0065	0.0023	0.90	0.82	-0.04	0.001	
	1.14044	Predicted	0.0027	0.0000	0.0099	0.0028		0.02		0.001	

506 Notes: $R^2 = coefficient of determination; E = coefficient of efficiency of Nash and Sutcliffe; RMSE = Root Mean Square Error; CRM = Coefficient of Residual Mass.$

507 When D_c was regressed on the shear stress τ using equation (6), the slope (the rill erodibility K_r) and intercepts (the critical shear stress τ_c) of soils were different among the 508 tree species. These equations had coefficients of regression (R^2) between 0.48 and 0.52, 509 510 always significant at p < 0.05 (Table 8 and Figure 5). The soils with C. betulus and P. *persica* showed the maximum (0.0025 s m⁻¹) and minimum (0.0019 s m⁻¹) values of K_r , 511 512 respectively, corresponding to the minimum (0.28 Pa) and maximum (0.42 Pa) values of τ_c . 513 K_r of the soil with C. betulus soil was 1.04, 1.19, and 1.31 times greater than Q. 514 castaneifolia, P. taeda, and P. persica soils, while τ_c of soils under P. persica was 1.5, 1.3, 515 and 1.1 times the values of C. betulus, Q. castaneifolia, and P. taeda, respectively (Table 516 8).

517





Figure 6 - Linear regression equations between the rill detachment capacity and the shear stress to estimate the rill erodibility and the critical shear stress in forest soils sampled under four tree species in Saravan Forest Park (Northern Iran) (n = 25 for each species).

523 Table 8 - Results of regression analysis between the rill detachment capacity (D_c) and the 524 shear stress (τ) to estimate the rill erodibility (K_r) and the critical shear stress (τ_c) in forest

soils sampled under four tree species in Saravan Forest Park (Northern Iran) (n = 25 for

526 each species).

527

	Linear regression	<i>K</i> _r	$ au_c$	D ²
Tree species	equation (6)	$(s m^{-1})$	(Pa)	Λ
C. betulus	$D_c = 0.0025 \ \tau - 0.0007$	0.0025	0.28	0.52
Q. castaneifolia	$D_c = 0.0024 \ \tau - 0.0008$	0.0024	0.33	0.52
P. persica	$D_c = 0.0019 \ \tau + 0.0008$	0.0019	0.42	0.47
P. taeda	$D_c = 0.0021 \ \tau - 0.0008$	0.0021	0.38	0.48

528 529 Note: R^2 = coefficient of determination.

530 4. Discussions

531

532 4.1. Effects of the tree species on soil properties and rill detachment capacity

533

The present study has explored whether four dominant tree species are able to induce changes in the erodibility of forest soils with homogenous texture (silty clay loam class) and similar properties (which are presumably due to the same forming processes and similar parent materials, Foth et al., 1990). Given this soil homogeneity, the plant survival and growth dynamics of the four tree species, combined with some practices used in this forest (such as forest improvement, timber harvesting, prescribed burning, and thinning), may explain the surveyed variations in the soil properties and rill detachment capacity.

541 The higher bulk density values and the lower aggregate stability of the soil with C. betulus 542 could be due to the root system characteristics of this species. C. betulus has few surface 543 roots (low weight density), which are responsible for a decrease in organic matter, strongly 544 linked to the properties mentioned above. This is also confirmed by the correlation analysis, 545 showing that, when the organic matter of soil increased, root system biomass and aggregate 546 stability also increased. Conversely, soils with P. persica, which have a considerable 547 surface roughness and structure (Viles et al., 1990; Gyssels et al., 2005), showed a higher 548 root system biomass, organic matter content, and aggregate stability. Moreover, in these 549 soils the bulk density was found to be lower, because the roots contribute to create a system 550 of continuous pores (Gyssels et al., 2005, Angers and Caron, 1998; Shinohara et al., 2016). 551 This result is in accordance with Shinohara et al. (2016) and David (2000), who showed 552 that soil bulk density decreases with the presence of plant roots. Also Li et al. (1992; 1993)

553 reported that fine roots less than one mm in diameter can significantly decrease the bulk 554 density of soil and increase soil porosity). Furthermore, soil bulk density mainly depends 555 on root diameter. As found by Meek et al. (1992), an increase in fine roots (less than one 556 mm) implies a decrease in bulk density, while larger roots work in the opposite direction, 557 which is consistent with several studies (e.g., Gyssels et al., 2005; Mamo and Bubenzer, 558 2001a; 2001b). In general, it has been demonstrated that species with high root density have 559 the highest potential to reduce soil erosion rates by concentrated flow (De Baets et al., 560 2007).

561 The variability of the soil properties between the tree species having different root 562 characteristics confirms that plant roots play a key role in driving changes in the soil. This 563 leads to the conclusion that root density and structure, which vary among plant species, also 564 exert an influence on soil detachment (Wang et al., 2015; Zhang et al., 2013; Li et al., 565 2015). In general, it has been demonstrated that rill erodibility and soil detachment rates 566 decreased exponentially with root density (De Baets et al., 2007). More specifically, Wang 567 et al. (2018b) found that soil detachment capacity decreases exponentially with root system 568 biomass among two different types of root systems in grasslands. Li et al. (1991a) have 569 demonstrated that soils with Pinus tabulaeformis (a conifer) and Hippophae rhamnoides (a 570 typical tree and shrub in the Chinese Loess Plateau) show an exponentially decreasing trend 571 of soil detachment by rills with root density. Also Gyssels and Poesen (2003) indicated that 572 rill erosion decreases exponentially with increasing root densities of cereals and grasses in 573 the loess Belt of Central Belgium, which is probably due to the combined effect of roots 574 and shoots of vegetation on soil erosion. This influence results in noticeable changes in rill 575 detachment capacity, which in this study varied significantly among the four tree species. 576 The lowest root system biomass detected in soils with C. betulus explains the minor effect 577 of this species on soil resistance to rill erosion. Additionally, exposing the soil with C. 578 betulus to some management operations (e.g., prescribed burning, thinning) may have 579 contributed to reducing the rill detachment capacity of this soil.

The lowest value of rill detachment capacity measured in soils with P. persica may be due to the highest root system biomass, and this is consistent with the results of other studies (Bibalani et al., 2006; Abdi et al., 2010). The latter authors found that the characteristics of the root system of *P. persica* enhance the stability of slopes by increasing the shear resistance of the soil, and this usually helps to minimize the risk of shallow landslides. Other studies (Wang et al., 2015; Li et al., 1991a; Li, 1995) have also concluded that plant roots are very important in reducing soil detachment, and specifically rill erosion (De Baets 587 et al., 2005; Gyssels et al., 2005). The study by Wang et al. (2015) stated that plant roots 588 have the greatest effect on increasing soil resistance to erosion, compared with other 589 contributory factors. However, other investigations have shown that vegetation cover might 590 not be so important or is even insignificant for controlling rill erosion (De Baets et al., 591 2007; Wang et al., 2014a). The fine and fibrous roots of P. persica increase soil stability 592 and decrease its susceptibility to water erosion compared to the soils under other tree 593 species. Moreover, root system biomass is commonly used to explain the influence of plant 594 roots on soil detachment capacity. In this study, the highest root system biomass played 595 more pronounced effects on the rill detachment capacity of soils with P. persica compared 596 to the soils from the other tree species. The present study and the related literature indicate 597 therefore that, for reducing rill erosion rates in erosion-sensitive areas (such as semi-arid 598 forests) it is recommended to use plant species that develop a dense root network (i.e., with 599 fibrous roots, De Baets et al., 2007). Moreover, management actions targeted at soil stabilization should be prioritized in these forest ecosystems, and deforestation, especially 600 601 in *P. persica* areas, should be avoided to control soil erosion.

602 The correlation analysis and PCA confirmed the relationships between the most important 603 properties and erodibility of the experimental soils. These statistical techniques 604 demonstrated that, for the investigated tree species in forests, the rill detachment capacity 605 was directly associated with the root system biomass and aggregate stability of sampled soils. This result is in accordance with Li et al. (1992a), who found that plant roots 606 607 significantly increase soil's structural stability, and thus decreaseits erodibility. In other 608 words, when root system biomass and aggregate stability decrease, rill detachment capacity 609 increases.

610 Moreover, the three principal components provided by PCA individually synthesized the 611 physical properties, the textural characteristics and the rill detachment capacity of soils. The 612 clustering of soils in four groups (one for each tree species) showed a clear gradient 613 according to the physical properties of the soil. Also in the studies of Lucas-Borja et al. 614 (2020) and Shabanpour et al. (2020) - the latter carried out in the same environment - the 615 differences in soil properties among different land uses (abandoned farmland, intensive 616 cropland, grassland, forestland, and woodland) were evident, and well-differentiated 617 groups, one for each land use, were clustered. In this study, these differences went beyond 618 land uses (therefore the landscape scale) and down to a smaller spatial scale; this means that 619 rill detachment capacity is different not only among different land uses (as several studies 620 have demonstrated, e.g., Parhizkar et al., 202a; Shabanspour et al., 2020), but also among

with a specific but dominant tree species, since the latter induces significant 621 soils 622 variations in soil's physical properties due to the action of its root system. This means that 623 changes in soil properties, due to an individual tree species with its specific root actions, are 624 important drivers of soil detachability in forests. A large body of literature shows that roots 625 affect soil properties - such as infiltration rates, aggregate stability, water and organic 626 matter contents, and shear strength - all controlling soil erosion rates to various degrees, not 627 only in forests but in the majority of land uses (e.g., De Baets et al., 2007; Vogt et al., 1995; 628 Lu et al., 2020).

629 In addition to the effects of tree root systems, soil erosion (and, therefore, the detachment 630 component of this complex physical process) are influenced by other ecological 631 characteristics of forest plants that drive soil hydrology. For instance, trees are also 632 important in forest hydrology because of the interception of rainfall by their canopies, 633 which reduces beneath-canopy throughfall and, ultimately, runoff and soil loss (Yang et al., 634 2019). In this regard, P. persica, C. betulus and Q. castaneifolia, although deciduous, have 635 broad leaves that are arranged on the branches with a wide canopy, which increases 636 interception (Nasiri et al., 2012). Conversely, the needles of P. taeda have a lower surface 637 area that is not so effective at reducing canopy throughfall, but they do protect soil from the kinetic energy of intense storms, even in the wettest seasons. Moreover, the aboveground 638 639 biomass of tree species can also reduce the hydrological response of soils, increasing 640 hydraulic roughness and trapping sediments (Kervroëdan et al., 2018). All these 641 characteristics of trees must be taken into account in addition to their root system features, 642 when specific tree species have to be selected for erosion control.

643

644 *4.2. Relationships between rill detachment capacity, rill erodibility, and unit stream power*645

646 Beside root characteristics and other hydrological factors linked to individual tree species, 647 rill detachment capacity depends on the hydraulic characteristics of overland flow (Nearing 648 et al., 1991). The regression analysis carried out in this study confirmed that unit stream 649 power is a good predictor of rill detachment capacity. This high accuracy may be due to the 650 fact that unit stream power simultaneously takes into account the flow velocity and soil 651 slope, both influencing soil detachability due to overland flow (Parhizkar et al., 2020a). 652 These results are in accordance with several studies, showing that rill detachment capacity 653 by overland flow was closely related to flow characteristics, such as water discharge, shear 654 stress, stream power, unit stream power, and unit energy; thus, rill detachment capacity can

655 be estimated from one of these predictors (Nearing et al., 1991; Xiao et al., 2017; Li et al., 656 2019). Moreover, our results showed that, compared to the power equations identified in 657 the previous study for forestls (Parhizkar et al., 2020a), a logarithmic function was more 658 accurate at estimating the rill detachment capacity from the unit stream power for the 659 different tree species. However, there is no physical reason for this higher accuracy, since 660 our methodwas simply based on a "black-box" approach (Nearing et al., 1991), looking for 661 the most accurate equation and the best predictor of a hydrological variable. This approach is used in several environmental studies, where the combination of complex physical, 662 663 chemical and biological processes makes it practically impossible to create simulations on a 664 mathematical basis, apart from simple regressions with variable analytical forms. The 665 regression equations are site-specific, and must be calibrated and used in the same or a least 666 in a very similar environment. The models are very useful for those users who require an 667 order of magnitude of soil erodibility in a soil with a specific tree species.

668 The response curves of rill detachment capacity versus the hydraulic parameter chosen in 669 this study (unit stream power) showed that the coefficients of the regression equations were 670 very similar for three of the studied species (C. betulus, Q. castaneifolia, and P. taeda), 671 while P. persica had a higher intercept (that is, rill detachment capacity in the case of zero 672 stream power) and a lower slope (that is, rill detachment capacity increases less with unit 673 stream power compared to the other species). This is further proof that soil erodibility is influenced not only by its physical properties, but also by the ecological features of plants, 674 675 such as their root systems.

676 The rill detachment capacity of a soil due to overland flow is strictly linked to its rill 677 erodibility and critical shear stress, which are two of the most important variables reflecting 678 soil resistance to rill erosion (Nearing et al., 1989). In the context of the previous 679 discussion, it is important to evaluate the effects of tree species in forests on these 680 variables, which are highly sensitive input parameters of some process-based erosion 681 models (Wang et al., 2016), such as the Water Erosion Prediction Project (WEPP) (Laflen 682 et al., 1991). The regression equations set up in this study for the four tree species went in 683 this direction, because they are the algorithm on which the erosion component of WEPP is 684 based. Since rill erosion is the prevalent form in process-based erosion models, rill 685 detachment capacity and erodibility are key parameters for accurate predictions of erosion 686 (Wang et al., 2016; Nearing et al., 1989). Therefore, their quantification is important to 687 improve the prediction accuracy of the WEPP model applications in arid areas.

However, the predictive accuracy of these equations, although satisfactory, was not as high as the models developed by Parhizkar et al. (2020a) and Zhang et al. (2008). Both these studies found that the linear regression functions between soil detachment and shear stress were very high for several land uses, with coefficients of determination of up to 0.9. Our study relates to a different spatial scale, and this may have influenced the lower prediction accuracy of the developed equations.

- 694 Compared to the other tree species, *P. persica* showed the lowest rill erodibility and the 695 highest critical shear stress. This was an effect of the lowest rill detachment capacity, which 696 was due to the binding effect of roots (Wang et al., 2014a), and of the changes induced by 697 the root system on soil properties. In other words, the lower rill detachment capacity 698 detected in *P. persica* soils, which was due to the interactive effects of roots and soil 699 properties, also influenced the rill erodibility and critical shear stress, which were 697 mathematically associated with the rill detachment capacity.
- Among the root characteristics of all the tree specie, the density and diameter of *P. persica* provided the highest resistance of the soil to concentrated flow erosion. The lower rill erodibility in roots with a diameter lower than one mm, known as "effective" roots (Li et al., 1991b; 1992), was in accordance with previous studies, showing that these roots reduce concentrated flow erosion and thus decrease the soil detachment capacity (Li et al., 1991b; Li et al., 1995).
- 707

708 **5. Conclusions**

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710 The soil's physico-chemical properties (except soil texture and bulk density) and mean rill 711 detachment capacity were different among the soils with four tree species sampled in 712 Northern Iran. The soils with Parrotia persica and Carpinus betulus showed the lowest and 713 the highest rill detachment capacity, respectively. This means the research question about 714 the ability of the studied tree species with their root characteristics to reduce the rill 715 detachment capacity compared to other plants can be confirmed. The higher root system 716 biomass of Parrotia persica could have played a binding effect on the soil and improved its 717 aggregate stability, thanks to the higher organic matter content. Therefore, Parrotia persica 718 shows the highest capacity to protect soil against erosion. These results can support 719 ecological engineers in the choice of tree species that are best indicated for soil 720 conservation.

721 The most accurate equations to predict rill detachment capacity from unit stream power 722 were based on a logarithmic function for all the studied species. These equations are highly accurate for water flow rates over 0.0025 m s⁻¹; this suitability addresses the second 723 724 research question of this study. Rill erodibility and critical shear stress were lowest and 725 highest, respectively, in *Parrotia persica*; this confirms the higher soil protection capacity 726 against erosion of this species in comparison with the other plants. The proposed models 727 are simple but quite accurate for predicting rill detachment rates. These models are 728 particularly useful in ecological engineering applications, when the order of magnitude of 729 soil erodibility must be estimated and the most effective plant species must be selected. 730 However, further studies should be carried out to test the reliability of the suggested 731 equations in other environmental conditions.

732

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1071 SUPPLEMENTARY DATA







1074 Figure 1(SD) – Mean values of monthly temperature and precipitation measured at the 1075 nearest meteorological station (records of the last 20 years) in Saravan Forest Park (Iran).

Table 1(SD) - Flow characteristics in the experiments carried out for measuring the rill detachment capacity under four tree species in Saravan
Forest Park (Northern Iran).

	S	a	h	R	V	τ	0	Ø					
Experiment	$[m m^{-1}]$	$[I m^{-1} c^{-1}]$	[m]	[m]	$\int_{1}^{1} m e^{-1}$		$\frac{32}{1000000000000000000000000000000000000$	$[m e^{-1}]$	$[kg s^{-1} m^{-2}]$				
			լույ	[[m]	լուջ լ	[1 a]		[ms]	C. betulus	Q. castaneifolia	P. taeda	P. persica	
1		0.26	0.006	0.005	0.09	0.51	0.04	0.001	0.00001	0.00004	0.00006	0.00009	
2	•	0.35	0.007	0.006	0.14	0.59	0.08	0.001	0.00003	0.00007	0.00009	0.00010	
3	0.01	0.46	0.009	0.008	0.19	0.76	0.14	0.002	0.00005	0.00009	0.00015	0.00016	
4		0.57	0.010	0.009	0.26	0.89	0.23	0.003	0.00006	0.00011	0.00017	0.00019	
5		0.69	0.012	0.011	0.31	1.05	0.32	0.003	0.00008	0.00013	0.00015	0.00027	
6		0.26	0.005	0.004	0.13	0.88	0.11	0.003	0.00011	0.00022	0.00034	0.00039	
7		0.35	0.006	0.005	0.19	1.07	0.20	0.004	0.00027	0.00038	0.00047	0.00059	
8	0.02	0.46	0.008	0.007	0.25	1.36	0.34	0.005	0.00044	0.00057	0.00066	0.00077	
9		0.57	0.009	0.008	0.31	1.55	0.48	0.006	0.00062	0.00069	0.00078	0.00089	
10	-	0.69	0.011	0.010	0.36	1.94	0.69	0.007	0.00086	0.00091	0.00099	0.00150	
11	0.03	0.26	0.004	0.004	0.19	1.07	0.20	0.006	0.00100	0.00160	0.00190	0.00250	
12		0.35	0.005	0.005	0.23	1.42	0.32	0.007	0.00130	0.00190	0.00290	0.00360	
13	1	0.46	0.007	0.006	0.29	1.79	0.52	0.009	0.00160	0.00220	0.00350	0.00390	
14		0.57	0.008	0.007	0.37	2.12	0.78	0.011	0.00190	0.00240	0.00370	0.00410	

15		0.69	0.010	0.009	0.42	2.67	1.12	0.013	0.00230	0.00260	0.00390	0.00440
16		0.26	0.003	0.003	0.21	1.10	0.29	0.011	0.00320	0.00340	0.00430	0.00480
17	•	0.35	0.004	0.004	0.31	1.43	0.44	0.012	0.00350	0.00370	0.00470	0.00510
18	0.04	0.46	0.005	0.005	0.37	1.83	0.67	0.015	0.00380	0.00420	0.00490	0.00530
19	•	0.57	0.007	0.006	0.42	2.46	1.03	0.017	0.00420	0.00460	0.00550	0.00560
20	•	0.69	0.009	0.008	0.46	3.07	1.41	0.018	0.00440	0.00490	0.00570	0.00590
21		0.26	0.002	0.002	0.32	1.14	0.36	0.016	0.00490	0.00540	0.00590	0.00620
22	•	0.35	0.003	0.003	0.36	1.47	0.53	0.018	0.00510	0.00560	0.00620	0.00640
23	0.05	0.46	0.004	0.004	0.41	1.97	0.81	0.021	0.00540	0.00590	0.00650	0.00670
24	1	0.57	0.006	0.006	0.46	2.90	1.33	0.023	0.00560	0.00620	0.00670	0.00690
25		0.69	0.007	0.006	0.51	3.12	1.59	0.026	0.00580	0.00650	0.00740	0.00770

1079 Notes: $D_c = rill$ detachment capacity; h = flow depth; R = hydraulic radius; q = flow rate per unit width; S = slope gradient; V = average water flow velocity; $\tau = hydraulic$ shear

1080 stress; ω = unit stream power; Ω = stream power.