Plant roots reduce rill detachment and shallow instability in forest topsoils

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Abstract

The competition between tree and grass roots for water and nutrients under the canopies of forest species may reduce the grass cover and thus increase rill erosion and shallow instability up to the values that are typical of the bare soils. This study has carried out flume experiments at different soil slopes and water flow rates, in order to evaluate rill detachment capacity (D_c) and erodibility (K_r) as well as the stability factors of hillslopes with *Gleditsia caspica* L. (a Fabaceae species, commonly called 'Persian honeylocust', a local endemic tree of Northern Iran) in comparison to bare soils. The variability of D_c has been associated to soil aggregate stability and plant root characteristics as key descriptors of rill erosion and surface stability. D_c was significantly lower (-41%) in the soil under the canopies compared to the bare sites. This was due to the higher soil aggregate stability (+83%) as well as to the denser and more extended plant root system, as confirmed by the negative correlations between D_c and soil and root parameters including root total length, mass density and specific root length. K_r was instead similar for the two soil conditions. The root system of the surface soil layer also played a beneficial action for slope stabilization, increasing the mean safety factor between soils with *Gleditsia caspica* and bare soils to 1.52 (well over the threshold of 1.3 identifying possible shallow instability). However, this safety factor was the highest at the lower slopes (1.63), and decreased with slope down to 1.39 in the steepest soils. Overall, this study provides indications to land managers on how to contrast soil erosion and shallow instability in delicate forestlands under semi-arid conditions.

Keywords: aggregate stability; erosion; rill erodibility; root length density; root mass density; slope.

1. Introduction

Land degradation can affect different components of forest ecosystems, and mainly vegetation (e.g., plant death and biodiversity loss) and soil (e.g., erosion, surface landslides) (Salvati and Zitti, 2005; 2008). Soil erosion due to water is one of the most severe threats for forest soils, leading to several negative impacts on these delicate ecosystems. Erosion is a complex process, consisting of soil detachment, transport of particles downstream and off-site sedimentation. Soil detachment, as a key process in determining the soil loss at the hillslope scale, is the separation of particles from the soil matrix due to overland flow (Zhang et al., 2019). Beside raindrop impact (due to the kinetic energy of the rainfall), soil detachment is due to the drag force of the overland flow (Polyakov and Nearing, 2003; Aksoy and Kavvas, 2005) under the interrill and rill forms. Detachment due to rill erosion ('rill detachment') is one of the most important erosive processes on steeper slopes (Wang et al., 2014; Owoputi and Stolte, 1995), but it may also occur on gentler hillslopes. Moreover, this process is different between low flows and high flow rates (Zhang et al., 2002). Often, a severe erosion process also leads to soil surface instability (generally acting 1-2 metres below ground), resulting in small landslides with noticeable volumes of soil particles leaving hillslopes and being transported downstream to valley areas. Both surface and mass movements can lead to severe problems, such as damage to forest roads, huge amounts of soil losses in the site subjected to landslides, and damage to civil infrastructures downstream of this site (Blaschke et al., 2000; Neverman et al., 2023; Teixeira Guerra et al., 2017). Therefore, the evaluation of the most influential factors on both soil detachment capacity and surface instability is essential.

Plant root system is considered as one of the most important stabilizing factors against soil detachment and surface instability, since roots play a beneficial effect on soil aggregate stability (Bronick and Lal, 2005; He et al., 2023; Zeng et al., 2018), and, more in general, on soil hydrological characteristics (Ni et al., 2019; Luo et al., 2020; Zhao et al., 2023). The root system provides soil with organic residues and polyvalent cations. This effect binds fine particles into macroaggregates (thus being less exposed to rainsplash and overland detachment) (Demenois et al., 2018; Kumar et al., 2013; Pojasok and Kay, 1990). Moreover, the presence of roots in soils mechanically strengthens the surface layer, more or less acting as iron bars into reinforced concrete (Parhizkar et al., 2021b).

Different studies have proved that plant roots not only have a significant effect on slope instability by mechanical reinforcement of soil (Murgia et al., 2022; McGuire et al., 2016), but also contribute to reduce D_c (Liu et al., 2022; Shabanpour et al., 2020; Yu et al., 2014). However, in ecological engineering, the importance of mechanical soil reinforcement and the anti-erosive effects of plants both depend on the different characteristics of surface soil and plant root system (Erktan et al., 2018; Li et al., 2017; Ng et al., 2020).

The mechanical reinforcement of surface soil due to the plant root system may be reduced under the canopies of trees. Under semi-arid climates, water shortage, mainly in the rhizosphere, is typical, as result of low precipitations and dry temperatures. This aridity this makes water in soil a limiting factor for plant growth and production, thus enhancing competition for water among different species and vegetation layers. Therefore, in the semi-arid areas, the shallow roots of trees may compete with roots of the herbaceous layer for water and nutrients (Craine and Dybzinski, 2013; Bombino et al., 2021; Ni et al., 2018), hampering the growth of grass. Small roots of grass play a noticeable influence on surface erosion and shallow instability of topsoil (Gadi et al., 2016; Ma et al., 2022a), while the thicker roots of trees instead govern the susceptibility of soil to mass erosion (Mamo and Bubenzer, 2001). Therefore, the competition between small roots of grass and surface roots of trees under the canopies may increase particle detachment and shallow instability of soils.

The Hyrcanian forests in Northern Iran are considered as one of most notable natural ecosystems, because of their high biodiversity (Fadaei et al., 2022). However, some inappropriate management operations and other human activities, such as past logging practices, and recent fraudulent fires (Parhizkar and Cerdà, 2023), have increased land degradation in this area. Soil erosion and shallow landslides have damaged the large variety of plant species as well as have compromised their importance for soil and water conservation in this forest ecosystem. This is the case of *Gleditsia caspica* L. (a Fabaceae species, commonly called ‘Persian honeylocust’), which is one of most important endemic tree in the Hyrcanian forests (Abedi and Pourbabaei, 2011). This species may noticeably help controlling soil erosion and surface instability for moderate to relatively steep slopes (between 25 and 35%) (Bibalani et al., 2006). However, the semi-arid climate of this area results in soil aridity, leading to competition between trees and grasses for water. Therefore, there is the need to explore whether this competition is able to increase rill erosion and shallow instability under canopies of *Gleditsia caspica* L. until the values that are typical of the bare soils.

To fill this gap, this study analyzes the rill detachment capacity (defined as the 'maximum value of the rill detachment rate' by Foster (1982), Govers et al. (2007) and Ma et al. (2022b), and hereafter indicated as 'D_c') as well as surface slope stability under the canopies of *Gleditsia caspica* L. in forestlands of Northern Iran with a specific focus on the surface root system characteristics. The specific objectives of the study are: (1) to evaluate the changes in D_c between soils with *Gleditsia caspica* L. and bare areas; (2) to analyze the relationships between D_c on one side, and soil aggregate stability (measured by the Mean Weight Diameter) and plant root characteristics on the other side; and (3) to investigate the effects of this species on slope stabilization. We hypothesise that competition between tree and grass roots under the canopies of *Gleditsia caspica* L. may increase rill erosion and shallow instability down to the minimum values of bare soil. The comparison of the rill detachment capacity and surface slope stability gives land managers insights about the beneficial effects of *Gleditsia caspica* L. species at improving soil resistance to surface erosion and instability for supporting soil conservation programs.

2. Materials and methods

2.1. Site description

The study area was the Saravan Forestland Park, Guilan Province, Iran (37°08′30″ N; 49°37′45″ E), which lies at altitudes from 50 to 250 m above the sea level and covers about 1500 hectares. The area has a Mediterranean climate with average annual temperature and rainfall of about 16.3 °C and 1360 mm, respectively (historical records of the last 20 years made available by the Iranian Meteorological Agency). The park drains northern and southern hillslopes (with profile slope in the range of 10% to 39%) in the Saravan watershed.

The prevalent soil texture is silty clay loam (on average 37.5% of clay, 49.9% of silt and of 12.6% sand). The soil type is Rendzine with brown calcareous soil (Mollisols category, Rendolls subcategory). More information about the geographical location of the study area can be found in previous works (Parhizkar et al., 2023a; Sedaghatkish et al., 2023).

The main land use in this area is forest, but many zones have been subjected in recent decades to several management actions, such as timber cutting and harvesting, prescribed burning, reforestation (also post-fire), and wetlands protection.

In the undisturbed area, the main tree species are *Alnus glutinosa* L., *Gleditsia caspica* L., *Parrotia persica* DC., *Pinus taeda* L. and *Fagus orientalis* L., while the prevalent shrubs include *Lycopus europaeus* L., *Nepeta involucrate* B., *Danae racemosa* L., *Smilax excelsa* L., *Urtica dioica* L. and *Plagiomnium cuspidatum* (Hedw.). These species cover more than half of the total study area (Abedi and Pourbabaei, 2011).

Among the main tree species, *Gleditsia caspica* L., a hardwood tree with height of even 12 m and a trunk covered by numerous branched spines, was selected, due its large cover in the area and its potential importance in stabilizing slopes in the study area, as mentioned above. Therefore, two experimental sites were identified, of which a first site was covered by this species (hereafter indicated as 'vegetated soil', that is soil with a tree layer of *Gleditsia caspica* L.) and the second site was bare ('bare soil') and assumed as control. The main topographic characteristics of the sampling sites were the following: aspect (North), mean altitude (93 m a.s.l.), slope gradient (10% to 40%).

2.2. Soil sampling and analysis

From March to April 2023, 280 soil samples (140 for each of the two experimental conditions of soil, vegetated or bare) were collected from the surface soil layer (0 to 20 cm) from both the vegetated site and the bare area, using a steel ring (0.1 m and 0.05 m in diameter and height, respectively). In the vegetated soil, seven samples were collected around each of 20 randomly selected trees (15-20 years old). In more detail, two quadrats (1.5 × 1.5 m and 2.5 × 2.5 m) were overlaid on the ground. Two samples were collected in the vertices of the diagonal of the first quadrat, and two others were collected in the vertices of the opposite diagonal of the second quadrat. Three additional samples were randomly collected immediately beside the trunk. This design allowed sampling in different positions (two opposite diagonals) and three distances from the tree (0, 2.1 and 3.5 m). After collection, the soil samples were transported to the laboratory for the flume experiments and measurement of the mean weight diameter (MWD) by the wet-sieving method (Kemper and Rosenau, 1986).

For soil sampling operations, only the upper layer of the rhizosphere was explored, since the focus of the study was the effects of the plant root system on soil erosion and instability of the topsoil. Indeed, the lateral roots of *Gleditsia caspica* L. develop in the topsoil, and form an intricate network, which is more or less parallel to the soil surface and may extend over a relatively long distance from the tree.

2.3. Measurement of plant root characteristics

An additional set of 60 soil samples (20 samples × 3 characteristics) was collected in 20 points of the same vegetated area, in order to measure the root characteristics of the surface soil layer, root total length (RLD) and dry mass densities (RMD) as well as specific root length (SRL). The choice of these root characteristics follows the indications of Forster et al. (2020), who showed that generally the first two characteristics are proxies of root distribution, and the specific root length indicates plant growth strategies. These root measurements were made following the guidelines by Delory et al. (2018) and using a cylinder (volume of 2 × litres, 0.1 m of height and 0.16 m of inner diameter) that was inserted at approximately 0.10 m of depth (measured on the top of the cylinder) immediately close to the soil samples collected around the tree trunk and used for flume experiments.

After sample collection, each cylinder was emptied, and the roots were gently washed with water. All roots were weighted and scanned in a film of water (Epson Perfection V850 Pro) with a resolution of 600 dpi. The software WinRhizo 2016 was used to measure the total root length and diameter. Then, the root samples were oven-dried and again weighed at temperature of 105 °C for 24 h. RLD and RMD were calculated as the ratios of total length and dry weight of roots, respectively, by the total volume of the cylinder (Forster et al., 2020), while SRL was the ratio between the total length and dry weight of roots.

2.4. Experimental design and measurement of rill detachment capacity

The rill detachment capacity was measured by experiments carried out in a hydraulic flume (3.5 m and 0.2 m in length and width, respectively) (Figure 1), whose specifications are fully described in the study of Ghasemzadeh et al. (2023) and summarized below.

Figure 1 - Experimental flume used to simulate rill detachment on soil samples collected in Saravan Forestland Park (Guilan Province, Iran).

The steel ring containing each sample collected in both vegetated and bare soils was placed in a test area at the downward side of the flume. The surface of each soil sample was sprayed with water for one day and a panel was used to cover this surface to prevent soil scouring during flow rate adjustments. Before measuring D_c, the water flow rate (Q, L m^{-1} s^{-1}) was measured by a graduated plastic cylinder until the desired value (0.44, 0.56, 0.64, 0.71, or 0.82 L m^{-1} s^{-1}), while the flume longitudinal slope or gradient (S, %) was setup to 8.1%, 16.8%, 23.7% or 31.9% using a hand lever. The mean value of experimental flow rates was selected after field measurements of overland flow produced by common rainfalls on the hillslopes of the areas. The other values were set according to previous studies (Parhizkar et al., 2021a). Unfortunately, the maximum bed slope simulated by the experimental flume was 38%, which hampered the simulation of rill detachment in steeper soils (where problems of rill erosion and soil instability may be severe). We cared simulating bed slopes higher than 30-32%, since, at this steepness, the water flow can become unstable and rollers in the water stream may occur, which may disturb the hydraulic conditions.

For each experiment (seven replications of one water flow and one slope value), the hydraulic radius was measured based on the rectangular cross section of the flume as well as the water flow depth and width in correspondence of the soil sample. The flow velocity (V_s) at the water free surface was estimated using a fluorescent dye technique in five replicated measurements (as for water flow rate). The flow characteristics, including the mean velocity (V), were estimated by the Reynold's number, calculated using the values of V_s. A reduction coefficient of 0.67, suggested by Abrahams et al. (1986) for laminar flow, was applied , the Reynolds' number always being lower than 1500. The experiment ended when the depth of the soil eroded from the steel ring was 0.015 m or after 5 minutes. After the experiment, the wet soil was oven dried at 105 °C for 24 h and then weighed.

Rill detachment capacity (D_c), erodibility (K_r) and shear stress (τ) were calculated by the equations of Table 1.

Table 1 - Equations and related measuring units used to measure soil erosion and stability parameters of the experimental soils (Saravan Forestland Park, Guilan Province, Iran).

Parameters	**Equation**	**Measuring unit**
Rill detachment capacity (D_c)	$D_c = \frac{\Delta M}{A \cdot \Delta t}$	kg s^{-1} m^{-2}
Rill erodibility (K_r)	$K_r = \frac{D_c}{\tau - \tau_c}$	s m^{-1}
Shear stress (τ)	$\tau = \rho g R S$	Pa
Safety factor (FS)	$FS = \frac{FS_v - FS_b}{FS_b}$	-

Notes: ΔM = dry weight of detached soil (kg); A = area of the soil sample (m^2); Δt = experiment duration (s); τ_c = critical shear stress (Pa); ρ = the water density (kg m^{-3}); g = gravity acceleration (m s^{-2}); R = hydraulic radius (m, assuming a rectangular cross section of the flume); S = longitudinal slope (m m^{-1}); FS_v = safety factor for vegetated soil; FS_b = safety factor for bare soil.

For each soil condition (vegetated or bare soil), each experiment (conducted in seven replicates) was a combination of four slopes (8.1%, 16.8%, 23.7%, and 31.9%) and five water flow rates (0.44, 0.56, 0.64, 0.71, and 0.82 L m^{-1} s^{-1}) (Table 1.SM).
Therefore, the experimental design consisted of two soil conditions (vegetated or bare soil) × four slope gradients × five water flow rates × seven replications, totaling 280 experiments.

2.5. Evaluation of slope stability

The safety factor is the ratio between the strength of the soil structure to load. A value of this safety factor below 1.3 requires a careful monitoring of the stability condition of slopes (Genet et al., 2010; Parhizkar et al., 2023b). In this study, the safety factor was calculated using the 'SLIP4EX' program (Genet et al., 2008) as a Microsoft® Excel® spreadsheet, based on Janbu method and the equation in Table 1. Janbu method is one of the most common geotechnical tools to estimate the slope stability. Compared to other methods (e.g., Bishop, Fellenius, Simple, etc.), Janbu equations are relatively simpler (less requirements of input parameters), and allow considering the effects of vegetation on slope stability. In more detail, SLIP4EX software modelled both vegetated and bare slope profiles. As input parameters, according to the SLP4EX manual, the specific weight (16 kN/m^3, as the mean weight of the 60 soil samples, whose volume was known), slope (15° measured by a clinometer), cohesion (4 kN/m^2), friction angle (30°) of soil (measured by geomechanical methods on soil samples for vegetated and bare soils) and available root force (in vegetated slopes, 2 kN/m) were adopted as input parameters. The values of the cohesion and friction angle were derived from data reported in a design of electric towers previously installed in a close area (Parhizkar et al., 2020c). The value of the available root force, according to the manual, was calculated as the product of root diameter by its number, estimated in the 60 samples used for root system analysis, and by the ultimate pullout resistance (8 MN/m^2), as suggested by the manual. According to (Greenwood et al., 2003), a partial safety factor of 8 was also applied to allow for uncertainty in root distribution and incompatibility of failure strain between the root and the soil.

Based on the values of safety factor calculated for bare and vegetated soils (FS_v and FS_b, respectively), a relative safety factor (FS) was calculated as the ratio between FS_b and FS_v (Table 1).

2.6. Statistical analysis

A one-way ANOVA was applied to MWD and D_c (response variables) adopting the soil condition as factor. Previously, the homogeneity of variances was verified, and the normality of sample distribution was checked by QQ-plots. The data was subjected to square root transformation, when required. A pairwise comparison using Tukey's test ($p < 0.01$) was applied to identify the differences in the response variables between vegetated and bare soil.

A Principal Component Analysis (PCA) was applied to identify possible correlations among D_c, MWD (for both soil conditions) as well as the root characteristics (for the vegetated soils) as well as the existence of a synthetic indicator replacing these variables.

All statistical analyses were conducted using XLSTAT 9.0 software (Addinsoft, Paris, France).

3. Results

Water flow depth was in the range 0.32 - 0.98 cm for the experimental water flows and flume bed slopes, while the flow velocity varied between 0.32 and 0.91 cm s^{-1}. The minimum and maximum hydraulic radius were 0.31 and 0.89 cm, respectively. The shear stress was in the range 4.4 - 20.4 Pa (Table 1.SM).

3.1. Plant root characteristics

RLD was in the range of 115 to 456 m m^{-3}, while its mean was 286 m m^{-3}. This range may be presumably affected by overestimation, due to the small size of sampler. RMD was on average 85.1 ± 25.8 g m^{-3}, while the lowest and highest values were 35.7 and 120 g m^{-3}. SRL was between 1.1 and 14.4 m g^{-1}, and its average value was 7.08 ± 3.59 m g^{-1} (Figure 2).

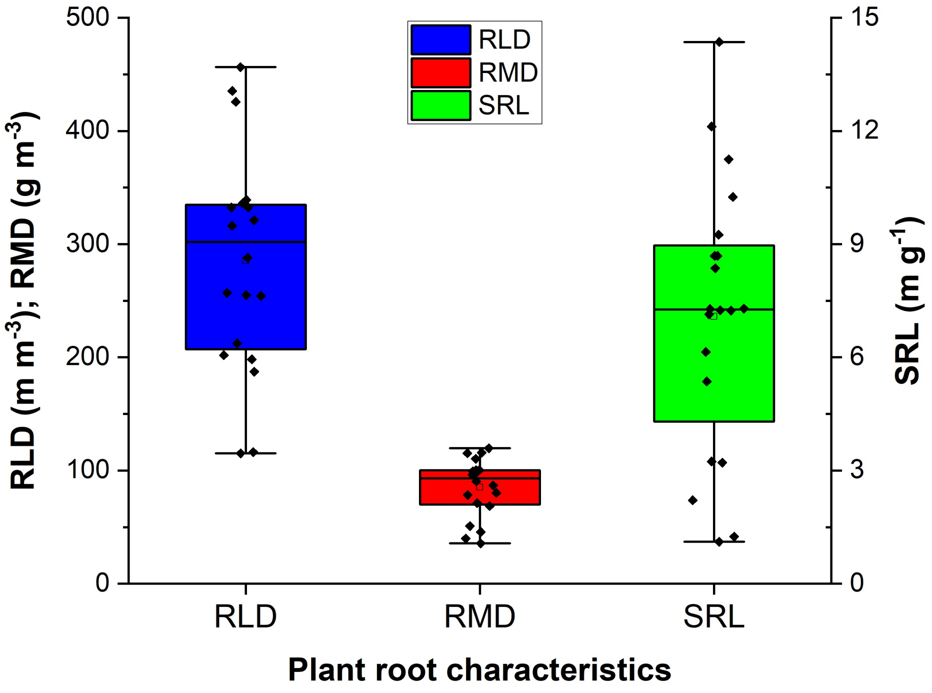

Figure 2 – Boxplot of plant root characteristics measured on soil samples collected in Saravan Forestland Park (Guilan Province, Iran).

Legend: RLD = Root Length Density; RMD = Root Mass Density; SRL = Specific Root Length.

3.2. Aggregate stability in vegetated and bare soils

MWD in vegetated soils was significantly ($p < 0.01$) higher compared to bare areas. In more detail, MWD of the vegetated soils was on average 0.65 ± 0.13 mm, 1.83-fold the value measured in the bare sites (0.35± 0.11 mm) (Figure 3).

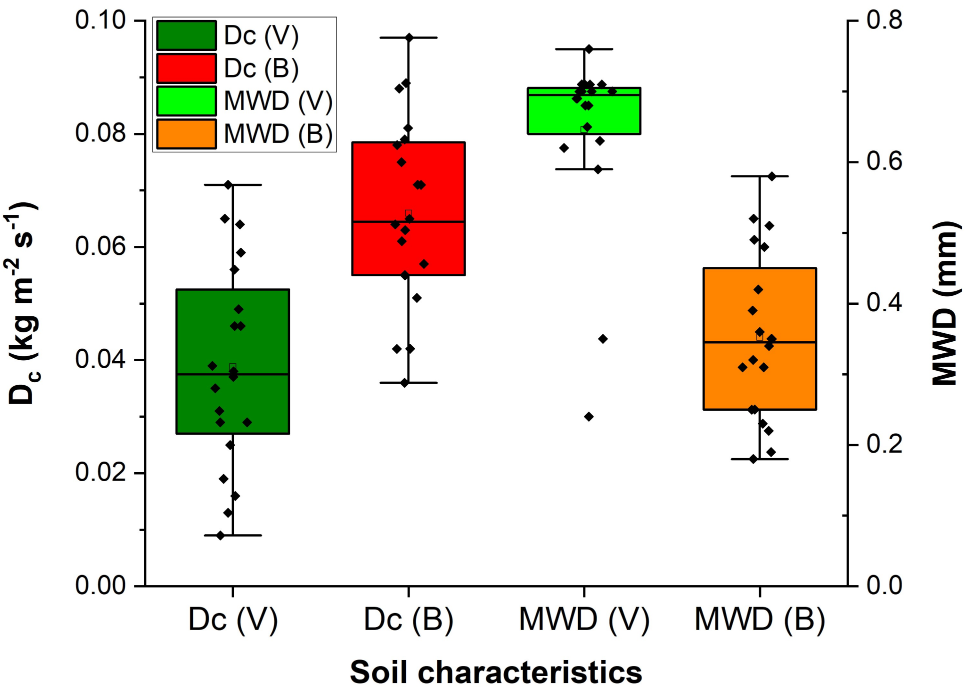

Figure 3 - Mean Weight Diameter (MWD) of aggregates and rill detachment capacity (D_c) measured in soils with *Gleditsia caspica* L. (vegetated soil, V) and bare soils (B) in Saravan Forestland Park (Guilan Province, Iran). Mean values of MWD and D_c are significantly different between the two soil conditions after Tukey's test ($p < 0.01$).

3.3. Rill detachment capacity in vegetated and bare soils

Significant changes in D_c between bare and vegetated soils were measured in the flume experiments at different slopes and water flow rates. D_c of bare soil was significantly ($p < 0.01$) higher compared to the values measured in the vegetated soils (0.066 ± 0.017 kg m^{-2} s^{-1} against 0.039 ± 0.018 kg m^{-2} s^{-1}, respectively). The values of D_c were in the range 0.036 to 0.097 and 0.009 to 0.071 kg m^{-2} s^{-1} for bare and vegetated soils, respectively (Figure 3).

3.4. Correlations among plant root characteristics and soil parameters

As expected, Pearson's matrix revealed significant ($p < 0.01$) and positive correlations among the root parameters ($r > 0.64$, with a peak of 0.86 for the pair RMD vs. SRL). D_c showed a negative correlation with MWD ($r = -0.70$), and was also inversely correlated with RLD ($r = -0.59$), RMD ($r = -0.82$) and SRL (-0.68) (Table 2).

Table 2 - Pearson's correlation matrix among root characteristics and soil parameters under the canopies of *Gleditsia caspica* L. in Saravan Forestland Park (Guilan Province, Iran).

	RLD	*RMD*	*SRL*	*MWD*	*D_c*
RLD	1	0,976	0,893	0,843	-0,766
RMD		1	0,889	0,831	-0,727
SRL			1	0,794	-0,742
MWD				1	-0,636
D_c					1

Notes: D_c = rill detachment capacity; RLD = root length density; RMD = root mass density; SRL = specific root length; MWD = Mean Weight Diameter of soil aggregates. All values are statistically significant ($p < 0.01$); green and red colours indicate positive and negative values, respectively.

The PCA provided one Principal Component (PC1), which alone explained 85% of the total variance of the original variables, which were associated with very high loadings (> 0.834) to this derivative variable. While the loading of D_c on PC1 was negative (-0.834), the other original variables (root characteristics and MWD) had positive loadings. In more detail, the loadings of RLD, RMD, SRL and MWD om PC1 were 0.975, 0.964, 0.939 and 0.892, respectively. This means that PC1 had high values, when D_c decreased, and RLD, RMD, SRL and MWD increased.

Therefore, PC1 may be considered as a synthetic indicator of soil resistance to particle detachment, as response variable to both MWD and plant root characteristics. The highest PC1 (3.12 ± 0.42) was estimated at the lowest slope of 8.1%, while the lowest (0.33 ± 0.59) at the steepest soil (31.9%). This resistance was a much narrower range (-1.71 ± 0.09, slope of 8.1%, to -2.08 ± 0.23, 31.9%) in bare soil (Figure 4).

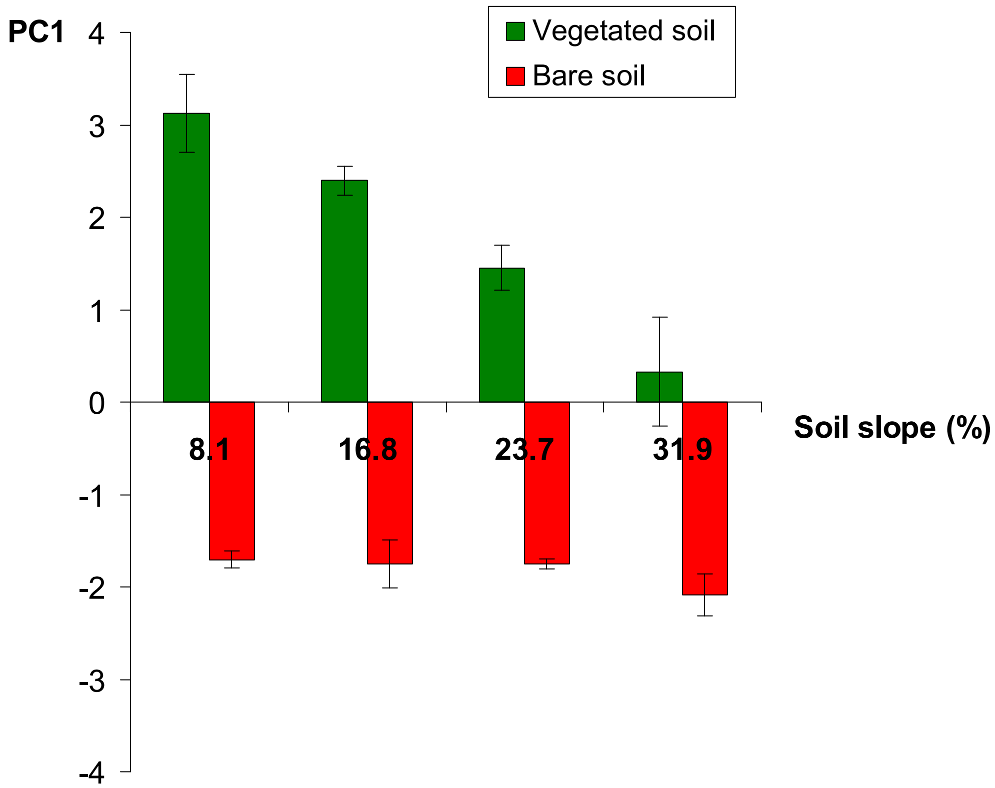

Figure 4 – Values of the first Principal Component (PC1) calculated on root characteristics and soil parameters under the canopies of *Gleditsia caspica* L. in Saravan Forestland Park (Guilan Province, Iran) for different slopes. Different letters indicate significant differences between means after Tukey's test ($p < 0.01$).

3.5. Estimation of rill erodibility

The regression analysis between D_c and τ showed very high coefficients of determination for the interpolating lines (r^2 of 0.91 for both vegetated and bare soils, $p < 0.01$). The slope of the interpolating lines (rill erodibility, K_r) was very similar between vegetated and bare soils, 0.0035 s m^{-1} in bare soil, and 0.0038 s m^{-1} in vegetated soil (Figure 5).

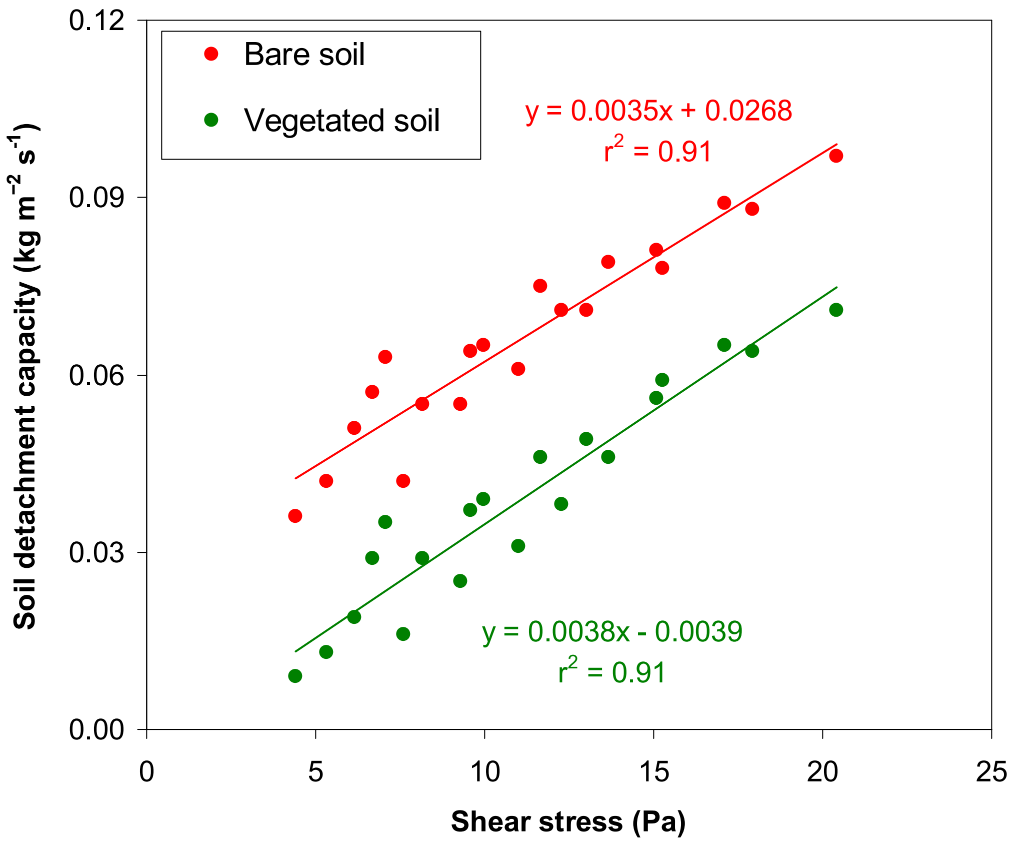

Figure 5 - Linear interpolation of rill detachment capacity and shear stress estimated by flume experiments on vegetated and bare soils sampled in Saravan Forestland Park (Guilan Province, Iran). The slope of the interpolating lines is the rill erodibility (K_r).

3.6. Safety factor of hillslopes

The mean FS of hillslopes was 1.52 and 1.02 for vegetated and bare soils, respectively. The highest (1.63) and lowest (1.39) values of FS_v (safety factor for the vegetated soil) were estimated at the lowest (8.1%) and highest (31.9%) slopes (Figure 6).

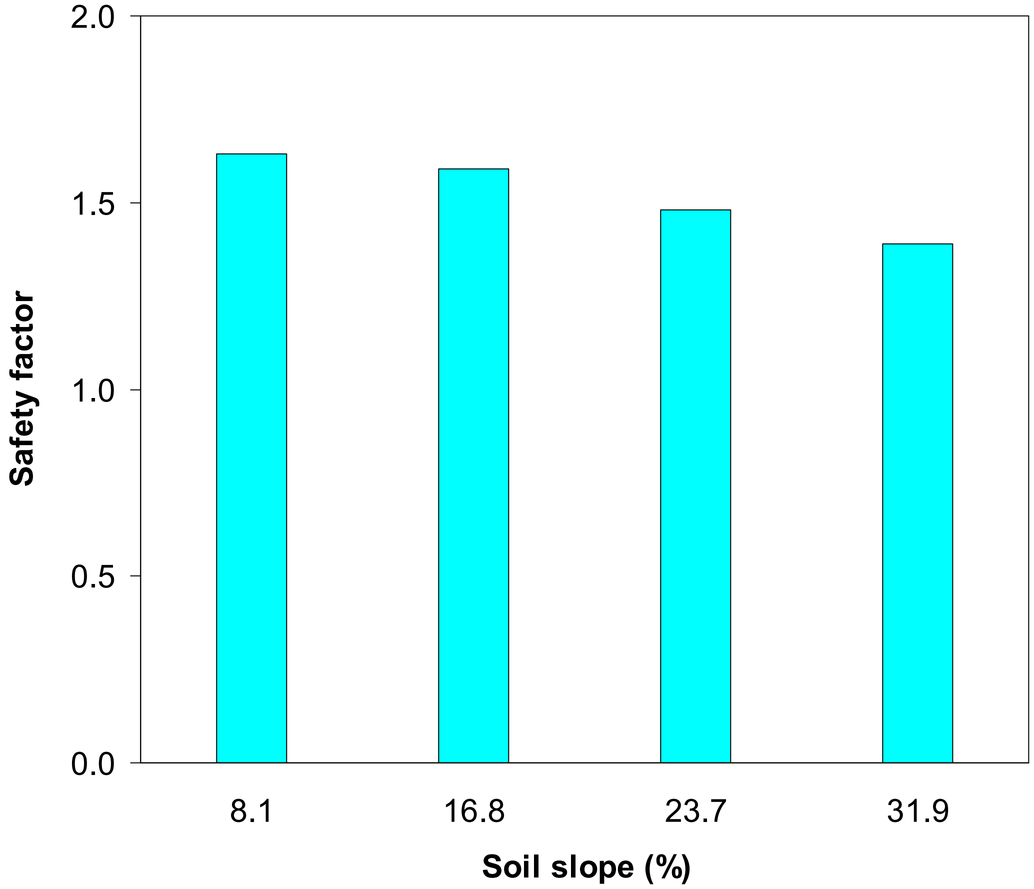

Figure 6 – Values of the safety factor of hillslopes with *Gleditsia caspica* L. in Saravan Park (Guilan Province, Iran).

4. Discussions

4.1. Influence of the root characteristics on soil aggregate stability and rill detachment capacity

Previous studies have demonstrated that, despite the different characteristics of plants, roots are able to improve soil aggregate stability (e.g., Li et al., 2020; Vergani and Graf, 2016; Greinwald et al., 2021; Xiao et al., 2020). The results of this investigation are in line with these findings, since a high and significant increase (on average by 83%) in MWD was measured between the sites with *Gleditsia caspica* L. and the bare soils. This increase in MWD is closely associated to the characteristics of the plant root systems, as shown by the high coefficients of correlation between MWD on one side, and the root parameters ($r > 0.79$). This association is consistent with the findings of Erktan et al. (2016), who reported a positive correlation between root mass and length density on one side, and soil aggregate stability on the other side, using a principal component analysis as in this study. Also Xiao et al. (2020) showed a positive and significant correlation between the specific root length and MWD. This relation may be explained by the fundamental role of roots, among plant traits, in strengthening the physical bonds between soil particles and thus in entrapping soil particles (Ali et al., 2023; Hudek et al., 1995). Therefore, the changes in soil MWD or alternative indicators must be carefully considered by land managers charged for soil conservation purposes (Zema et al., 2023), since an increase (or a decrease) in the MWD due to modifications in soil evolution and management (e.g., in deforested or wildfire-affected areas) can reduce (or increase, in the case of MWD reduction) the resistance of soils to detachment by water.

In this regard, the flume experiments clearly evidenced that, compared to the bare soils, the vegetated sites showed significantly lower D_c (-41.2%). Since no other differences characterise the two experimental conditions, this increase can be ascribed to the higher values of MWD under the canopies of *Gleditsia caspica* L. trees with their well-developed root system. In other words, the removal of *Gleditsia caspica* L. species in the studied forest ecosystem, due to unsuitable management practices and intense human activities, resulted in a decrease in soil aggregate stability and, as a consequence, in an increase in rill detachment capacity. Also this result agrees with other investigations, demonstrating that this soil property noticeably influences D_c. For example, Peng et al. (2022) reported that D_c exponentially decreases with increasing MWD and, therefore, the soil resistance to erosion is indirectly correlated to soil aggregate stability. Moreover, Torri et al. (1998) demonstrated that MWD can be used to effectively simulate the rill detachment capacity. Clearly, the significant differences in MWD and D_c between bare and vegetated soils are a response to the analysed root system parameters. These differences lead to discriminate the two soil conditions in terms of soil resistance to particle detachment due to the overland flow, as demonstrated by the Principal Component Analysis. It is worth mentioning that, since PC1 is a meaningful proxy of soil resistance to rill detachment as well as to the associated soil aggregate and root characteristics, the values of PC1 indicate that this soil resistance in sites with plant roots significantly decreases when soil slope increases. Therefore, there may be a threshold slope that makes ineffective the plant root action against erosion, and this would require other anti-erosive techniques. This threshold slope may be identified by increasing the soil slope for vegetated conditions until shallow instability is observed. In contrast, the resistance to erosion does not significantly vary with slope in bare soils.

4.2. Influence of plant root system on rill erodibility

Our study found the same rill erodibility (K_r) in bare and vegetated soils. At a first sight, this result may be surprising for two reasons: first, since D_c is different between the two soil conditions, a different K_r would also be expected; second, this finding is not consistent with the results of other studies. More specifically, Hao et al. (2021) reported that plant roots strongly promote soil cohesion, and thus reduce K_r. Moreover, Parhizkar et al. (2021b) showed that, by the direct influence of roots, K_r was lower by about 80% in sites with plants compared to bare soils. However, these authors did not analyse the key role of soil aggregate on rill detachment capacity. We explain this apparently surprising result by the similar variability in both D_c and τ, which makes the rill detachment capacity per unit shear stress comparable (and therefore also rill erodibility). In other words, since K_r is the slope of the line interpolating D_c and τ, and the variability is very similar, it is possible that K_r is practically equal between the two soil condition. Moreover, the high accuracy of the proposed linear model for estimating K_r in both soil conditions is consistent with the findings of Zhang et al. (2008), who showed that the shear stress is a suitable hydraulic parameter for calculating K_r. Also other authors, working in the same experimental conditions, reported high coefficients of determination in regressions between D_c and τ to estimate K_r (Parhizkar et al., 2021d, e)

All these parameters, which reflect soil resistance to runoff (Nearing et al., 1989), are sensitive input variables in process-based erosion models (Wang et al., 2016; Knapen et al., 2008), such as the WEPP model (Laflen et al., 1991), where an accurate estimation of rill erodibility is a prerequisite for reliable erosion predictions on steep slopes (Parhizkar et al., 2020c).

4.3. Influence of plant root system on shallow instability of soil

In recent decades, the need to better understand the role of plant roots on shallow stability has gained increased attention, as shown by several studies (Abdi et al., 2010; Löbmann et al., 2020; Reubens et al., 2007). This is due to the fact that the specific plant species in forest ecosystems, such as in Saravan Forestland Park, determine different environmental conditions for tree growth with complex reinforcement mechanisms, due to the different characteristics of the root system (Masi et al., 2021; Mattia et al., 2005). Many areas of the studied forest are susceptible to rill erosion, as reported in previous works (Parhizkar et al., 2020b, 2021c), with rills gradually expanding on hillslopes with different profile slopes. The safety factors calculated in sites with and without *Gleditsia caspica* L. prove that surface roots effectively increase surface stability of hillslopes, thanks to soil reinforcement (Burylo et al., 2011). It should be also evidenced that the effects of this reinforcement decrease with increasing slope, being the FS of the milder profiles (8.1%) higher by 17.3% compared to the steeper hillslopes (31.9%). If the reinforcement effects of vegetation decrease with increasing slopes, there would be the possibility of reinforcement strategies other than reforestation with native species on hillslopes that are steeper than the maximum slope explored in this study, where the safety factor may be lower than 1.3 or even than one.

5. Conclusions

The flume experiments at different profile slopes and water flow rates showed a significantly higher rill detachment capacity in soil samples collected in sites with *Gleditsia caspica* L. (an endemic tree species of Northern Iran) compared to bare soils. This higher resistance to rill erosion is due to the increase in soil aggregate stability, which results from the beneficial effects of surface root system. A negative correlation between D_c on one side, and soil MWD and plant root characteristics on the other side was also found, and this supports the associations among soil erodibility, and the studied soil and plant parameters. Rill erodibility, which is the slope of the line interpolating D_c and shear stress, was similar between the two soil conditions, resulting from the simultaneous variability in these parameters. The root system in the surface layer also played a beneficial action for slope stabilization, and this action was more effective at the lower slopes. Overall, the results of this study highlight the effectiveness of roots in forests of *Gleditsia caspica* L. to improve the soil resistance to both rill erosion and shallow instability, especially at low to intermediate slope profiles. Overall, the working hypothesis that competition between tree and grass roots under the canopies of *Gleditsia caspica* L. may increase rill erosion and shallow instability down to the minimum values of bare soil may be rejected, at least for this native species of Hyrcanian forest.

Further research should explore: (i) the root actions of other widely-spread native species in the area, having the potential of slope stabilisation and erosion mitigation (e.g., alder tree, *Alnus glutinosa*, widely distributed in the North of Iran, and maple tree, *Acer velutinum* Boiss., one of the first woody species that establishes naturally and grows in the Caspian forests); (ii) the effects of these vegetal species on hillslopes that are steeper compared to the maximum value simulated in flume experiments, possibly through field investigations.

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SUPPLEMENTARY MATERIAL

Table 1.SM – Main hydraulic parameters in the flume experiments to measure rill detachment capacity in soils with *Gleditsia caspica* L. and bare soils in Saravan Park (Guilan Province, Iran).

Soil slope (S, %)	Flow rate (q, L m^{-1} s^{-1})	Flow depth (h, m)	Hydraulic radius (R, m)	Flow velocity* (V, m s^{-1})	Shear stress (τ, Pa)	Rill detachment capacity (D_c, kg s^{-1} m^{-2})	
						bare soil	vegetated soil
	0.44	0.0059	0.006	0.32	4.422	0.036	0.009
	0.56	0.0072	0.007	0.41	5.331	0.042	0.013
8.1	0.64	0.0084	0.008	0.49	6.151	0.051	0.019
	0.71	0.0092	0.008	0.56	6.688	0.057	0.029
	0.82	0.0098	0.009	0.63	7.072	0.063	0.035
	0.44	0.0048	0.005	0.43	7.601	0.042	0.016
	0.56	0.0060	0.006	0.53	9.305	0.055	0.025
16.8	0.64	0.0072	0.007	0.61	11.001	0.061	0.031
	0.71	0.0081	0.007	0.69	12.266	0.071	0.038
	0.82	0.0091	0.008	0.76	13.677	0.079	0.046
23.7	0.44	0.0036	0.004	0.51	8.157	0.055	0.029

	0.56	0.0045	0.004	0.60	9.980	0.065	0.039
	0.64	0.0059	0.006	0.70	13.023	0.071	0.049
	0.71	0.0070	0.007	0.76	15.255	0.078	0.059
	0.82	0.0080	0.007	0.83	17.105	0.089	0.065
	0.044	0.0032	0.003	0.61	9.576	0.064	0.037
	0.56	0.0039	0.004	0.71	11.648	0.075	0.046
31.9	0.64	0.0051	0.005	0.77	15.085	0.081	0.056
	0.71	0.0061	0.006	0.83	17.918	0.088	0.064
	082	0.0070	0.007	0.91	20.424	0.097	0.071

Note: * measured by the dye technique.