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Modelling Soil Detachment Capacity by Soil Properties and Root Diameter in Soils Under Tree Species in Northern Iran

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ABSTRACT

Aims: Root characteristics and soil properties can be used to predict soil detachment capacity (D_c). However, few investigations have explored the effects of root diameter and plasticity index on the rill erosion process, particularly for soils under mixed tree species modes.

Materials & Methods: To fill this gap, this study has evaluated the effects of root diameter, soil organic matter content, and plasticity index on the D_c in soils under mixed modes of *Crataegus ambigue, Fraxinus excelsior Linnaeus*, *Acer velutinum*, and *Pterocarya fraxinifolia* species, in planted forests of Guilan Province (northern Iran). Moreover, these three variables were used to propose a model for predicting soil detachment capacity. For measuring D_c, the slopes (6.5, 12.3, 18.4, and 26.1%) and water discharges (0.26, 0.34, 0.44, 0.52, and 0.65 L. $m^{-1}.s^{-1}$) were adjusted to the desired values using a laboratory flume with 3.5 and 0.2 m in length and width, respectively. These values were selected based on the field measurements of concentrated flows in the study area. Moreover, shear stress values were calculated using the hydraulic radius and the bed slope.

Findings: The results showed that when root diameter, soil organic matter, and plasticity index increase, D_c decreases in soils under the studied species ($p < 0.01$). These changes in the studied variables were confirmed by principal component analysis (PCA), which showed that root diameter and plasticity index influenced the first PC (loading over 0.50), and organic matter significantly influenced PC2 (loading 0.56) ($p < 0.01$).

Conclusion: The established model can predict the soil detachment capacity according to a linear multi-regression relationship of the selected variables. It may be helpful for hydrologists and land managers who require reliable estimations of soil detachment rates in forest soils.

Keywords: PCA; Multi-regression Equation; Organic Matter; Rill Erosion; Soil Conservation.

CITATION LINKS

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Introduction

Soil erosion refers to the detachment, transport, and deposition of soil particles due to rainfall and overland flow [1, 2]. In rill erosion, the detachment step is due to the overland and concentrated flow [3] and can contribute vastly to the overall erosion rate [4]. The maximum rate of detachment in rills, which is defined as "soil detachment capacity" (D_c) [5, 6], is a key parameter for estimating the rate of rill erosion resulting from overland flow. Accurate estimation of D_c is necessary for the calculation of other hydrological variables such as rill erodibility (K_r) and critical shear stress (τ_c) [7]. Among the different forms of soil erosion, rill erosion is considered one of the most prominent challenges in soil conservation. Various factors affect rill erosion, including flow discharge, slope gradient, scouring time, rainfall, runoff, soil, topography, vegetation, and microorganisms [8,9,10]. Therefore, quantifying the factors influencing the D_c is helpful for hydrological predictions using process-based erosion models [11]. In this regard, solutions exploiting the properties of soil and root characteristics can be useful [12,13].

As noted by many researchers, plant and tree roots can considerably improve soil properties and reduce soil detachment capacity [14,15,16,17]. Moreover, different characteristics of roots have been widely used to establish models to predict soil detachment capacity. For instance, Liu et al. [18] showed that D_c could be modeled by root surface area density and soil cohesion. Peng et al. [19] reported a linear model to predict soil detachment capacity based on root mass density and aggregate stability. As can be seen from these results, root characteristics, combined with soil properties, can be used to estimate soil detachment capacity. However, not all root characteristics have the same effect on soil detachment capacity. This is the case of root diameter, a characteristic of root that mainly influences soil detachment rates and has a high correlation with soil detachment by concentrated flow erosion [20]. In this regard, it is reported that roots with a diameter of less than one mm, known as "effective" root diameter, are effective in controlling concentrated flow and, thus, in reducing soil detachment rates [21, 22]. It should be mentioned that among the studied soil properties, organic matter is considered the most common property of soils that can contribute to model D_c [23], and abundant studies on the impacts of soil organic matter on this hydrological variable can be found in the literature [24, 25].

As unique ecosystems and essential habitats for significant plant species in Iran, Hyrcanian forests are known for the high floristic distribution of native species [26,27,28,29]. In these forestlands, various types of trees, shrubs, and local plants can effectively improve soil quality and protection [30]. Moreover, there are sites under mixed tree species in planted forests, which these species can affect soil properties such as soil organic carbon and nutrient accumulation [31]. However, studies on the effectiveness of mixed tree species in planted forests in improving soil properties and reducing soil detachment rates are lacking. Therefore, it is crucial to study the impacts of tree species roots on soil erosion.

Despite the large body of literature on the associations of soil properties such as soil organic matter and soil detachment rates in rills, very scarce attention has been paid to other physical characteristics of soil that may noticeably drive the soil detachment process in forest ecosystems. This is the case of soil plasticity, which is essential to engineers and scientists since it drives soil geo-mechanical properties [32]. This soil property is expressed by the 'plasticity index,' developed by Albert Atterberg, to classify the consistency of soils into different categories (named 'consistency

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limits'). The plasticity index is a valuable indicator of the mechanical behavior of fine-grained soils [33]. This indicator has also been found to be in close relationships with structural stability [34], which, in turn, dramatically influences soil resistance to erosion together with soil organic matter [35]. Despite these direct and indirect associations between the plasticity index on one side and the hydrological behavior of soils on the other, very scarce investigations have explored how and to what extent the plasticity index influences soil detachment capacity in rills. Clark and Wynn [33] compared different methods of determining critical shear stress and erodibility of soil, following a much older study by Smerdon and Beasley relating plasticity index and shear stress. To the authors' best knowledge, only two studies explored the correlation between soil plasticity and its susceptibility to erosion. Khoirullah et al. [37] related the plasticity index with the 'erodibility factor' of the Universal Soil Loss Equation ('USLE-K') to evaluate soil's resistance to erosion in Indonesia. Ngezahayo et al. [38] evaluated the influence of geotechnical parameters (including plasticity index) on the erodibility of rural roads by analyzing published data from over 200 studies from 36 countries. These isolated studies lack a better understanding of plasticity effects on soil detachment capacity. This need remains unsatisfied even in the case of rill erosion. The soil properties and root characteristics of different plant species, such as root diameter, may be a suitable way to model the soil detachment capacity and predict the rill erosion rates. In other words, changes in these two main variables lead to changes in soil detachment capacity in rills, leading to changes in the rill erosion rates. Predicting soil detachment capacity is required for rill erosion control, as it is a significant factor in the overall erosion process, especially in ecosystems prone to erosion. It helps land managers adopt suitable strategies for soil conservation. In this case, root diameter can be considered an innovation in this research. To fill this gap, the current study analyzes the impacts of the root diameter of four mixed species and plasticity index along with soil organic matter on soil detachment capacity caused by rills in planted forest lands in the north of Iran. The specific aims of the current study are (1) to evaluate the changes in soil detachment capacity (D_c) in soils under the *Crataegus ambigue*, *Fraxinus excelsior* Linnaeus, *Acer velutinum* and *Pterocarya fraxinifolia* species in different sites; (2) analyze the effects of the studied variables including root diameter, organic matter and plasticity index on D_c; and (3) propose a regression model to predict the D_c from these variables. We hypothesize that regression equation is proposed to predict D_c from the main soil properties and root diameter. The study contributes to understanding the relationships between soil erodibility, soil properties, and root systems in the forest ecosystem.

Materials & Methods

Study Area

The study area, known as Saravan Forest, with an area of 14.87 km^2, is a park in Guilan Province, Iran (37°07′25′′ N; 49°35′37″ E) (Figure 1), which extends in elevation from 50 to 250 m above the sea level. This area has a Mediterranean climate with average annual temperature and rainfall of 16.3 ˚C and 1360 mm, respectively [39]. Based on the study of Ghasemzadeh et al. [40] in the forestlands of this Province, the soil texture of the study area is silty clay loam. The investigated soil's mean clay, silt, and sand contents were 37.5%, 49.9%, and 12.6%, respectively. The bulk density also was 1287 kg.m^{-3}, while the soil aggregate stability in forest ecosystems and for different species ranged between

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0.41 ± 0.03 mm and 0.79 ± 0.02 mm. In Iran, deforestation in forest ecosystems is one of the most critical anthropogenic factors of soil erosion, especially in the northern part of the country with a high percentage of forests; deforestation is one of the significant factors causing severe soil erosion [41]. In the study area, some hillslopes inside the park were deforested due to the installation of high-voltage towers two to four years before the investigation, and this anthropogenic factor has caused severe rill erosion [42].

There are various plant and tree species in this forestland and adjacent forest areas, including *Acalypha australis*, *Azola filiculoides*, *Carex divolsa*, *Danae racemosa*, *Rubus persicus Boiss*, *Crataegus ambigue*, and *Hedera helix* [43]. To achieve the objectives of the study, four tree species, including *Crataegus ambigue, Fraxinus excelsior* Linnaeus*, Acer velutinum,* and *Pterocarya fraxinifolia* [44, 45], were selected in three sites (as sites with mixed modes of tree species). All conditions for the studied species in the three sites were the same to allow a more appropriate comparison of the D_c. In more detail, to create sampling zones with uniform characteristics, these sites were chosen according to the similarity in topography, growth years, slope, soil texture, distance, and management operations.

Soil Sampling, Experimental Design, and Measurement of Soil detachment Capacity

From January to April 2023, the experiment

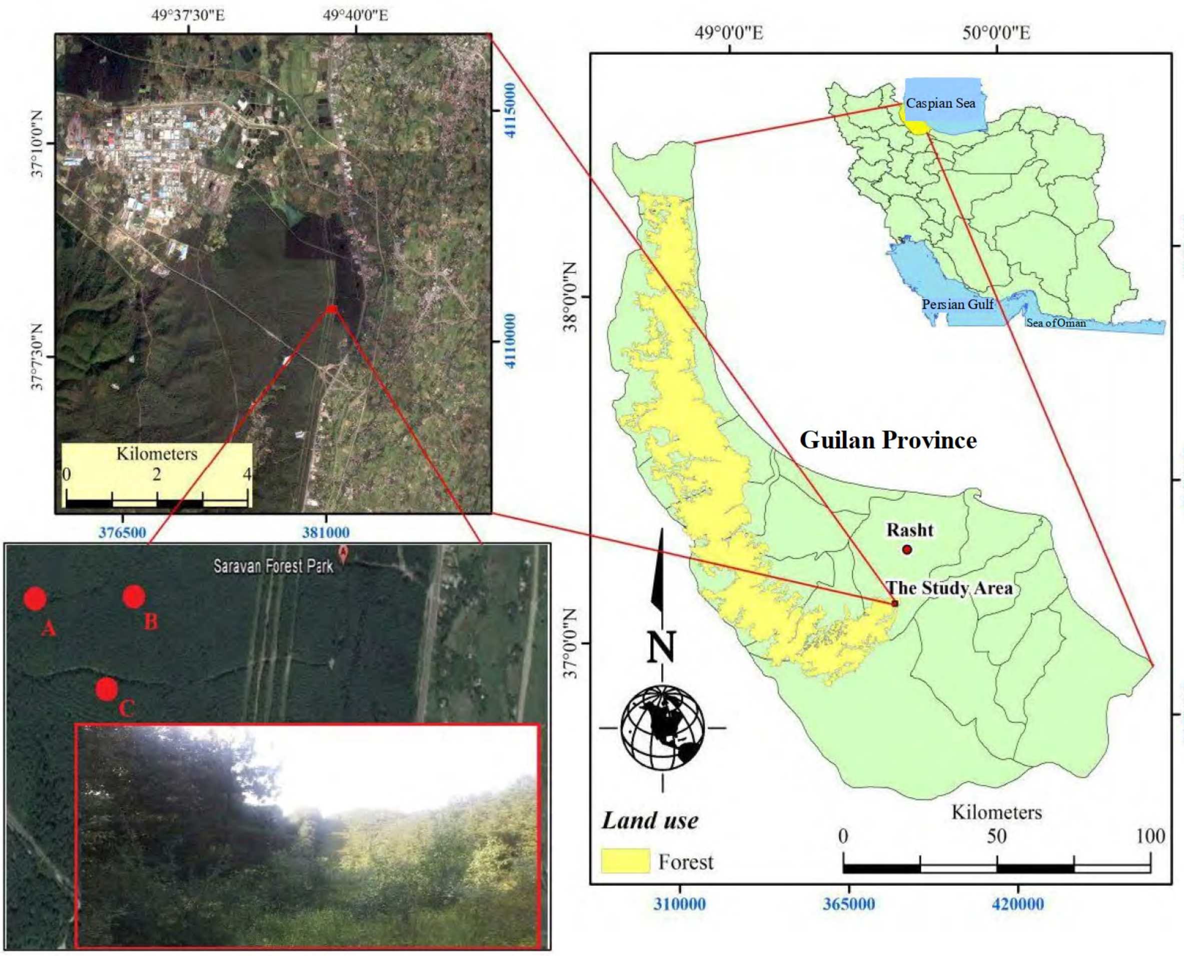

Figure 1) Geographical location of the study area and an aerial view of studied sites (from A to C) (Source: Google® Map®).

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was done in the Soil Laboratory of Guilan University, Iran. To start tests in the laboratory, the soil samples were extracted from the top 10 cm of the studied sites using a steel ring with a diameter of 0.1 m and a height of 0.05 m. Rill erosion is soil removal by concentrated water flow, and water moving over the surface will remove soil particles. Extracted soil samples with roots were inserted in the test area at the downward section of the hydraulic flume (3.5 and 0.2 m in length and width, respectively, whose specifications are fully described in the study of Parhizkar et al. [46]. After that, the surface of the soil sample was sprayed with water for one day and covered with a panel to prevent scouring during primary adjustments of the flume. The adjustments, including the water discharges (0.26, 0.34, 0.44, 0.52, and 0.65 $L.m^{-1}.s^{-1}$) and slopes (6.5%, 12.3%, 18.4%, and 26.1%), mean of flow velocity and water depth were determined using a graduated cylinder, slope adjustment lever, fluorescent dye method, and level probe, respectively [47]. For the calculation of mean flow velocity, the surface flow velocity of the water was corrected by the reported coefficients of Abrahams et al. [48]. All depth, velocity, and flow discharge measurements were repeated six times. The values of slopes and water discharges were selected based on the field measurements of concentrated flows in the studies of Parhizkar et al. [42] in the forestlands of this Province (Table 1). To minimize the influence of the steel ring's side wall on the soil detachment capacity values, the experiment was terminated when the scoured soil depth in the steel ring reached approximately 0.015 m or after five minutes [49]. Finally, the wet soil sample was extracted from the hole, dried at 105°C for 1 day, and then weighed. The layout of the laboratory flume, the experimental process, and the schematic of experimental design and field sampling are presented in Figure 2 and Figure 3, respectively. Overall, the experimental design consisted of three sites under different tree species × four slope gradients × five water discharges × five replications, totaling 300 experiments.

Soil detachment capacity (D_C, $kg.s^{-1}.m^{-2}$) with five repetitions was calculated using the dry weight of detached soil (ΔM, kg), scouring time (Dt, s), and the area of the soil sample (A, m^2), as shown in the following equation Eq. (1):

$$D_c = \frac{\Delta M}{A \cdot \Delta t} \qquad \text{Eq. (1)}$$

Moreover, flow shear stress (τ, Pa) was calculated using the following equation Eq. (2):

$$\tau = \rho g R S \qquad \text{Eq. (2)}$$

where r is the clean water density ($kg.m^{-3}$), g is the acceleration of gravity ($m.s^{-2}$), R is the hydraulic radius (m), and S is the bed slope ($m.m^{-1}$).

Measurement of Root Diameter and Soil Properties

Root diameter, organic matter content, and plasticity index were determined on an additional 180 soil samples (20 samples × 3 sites × 3 characteristics. These 20 samples were divided among the tree species, and five samples were selected for each tree species at each site. The root diameter was determined using a Vernier caliper. For this measurement, the soil was sampled in different positions and at three distances (0, 0.7, and 1.4 m) from the species by the studies of Zhang et al. [50] and Sedaghatkish et al. [45]. Moreover, soil organic matter and plasticity index were determined using the potassium dichromate colorimetric and Casagrande plasticity chart methods [51, 52].

Statistical Analysis

QQ plots were used to check the normality of sample distribution. Pearson's correlation matrix and Principal Component Analysis

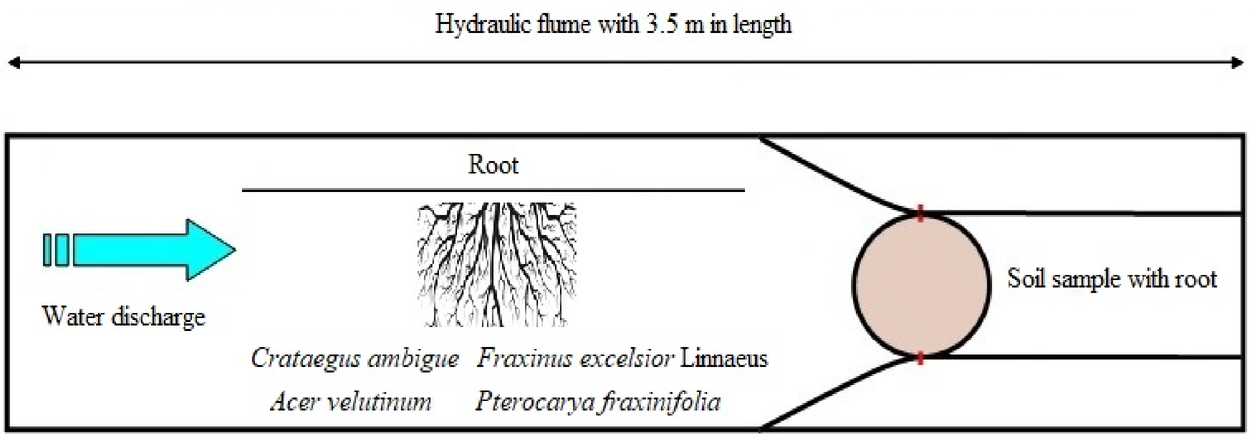

Figure 2) Layout of the laboratory flume and the experimental process.

Table 1) Values of the shear stress in the flume experiments for measuring the soil detachment capacity.

Experiment	Slope (S, %)	Water Discharge (q, L.m^{-1}.s^{-1})	Flow Velocity (V, m.s^{-1})	Shear Stress (τ, Pa)	Unit tream power (U, m.s^{-1})
1		0.26	0.059	2.685	0.0025
2		0.34	0.069	2.976	0.0029
3	6.5	0.44	0.075	3.549	0.0031
4		0.52	0.079	4.334	0.0033
5		0.65	0.080	4.936	0.0034
6		0.26	0.084	3.964	0.0082
7		0.34	0.087	4.970	0.0085
8	12.3	0.44	0.090	5.958	0.0088
9		0.52	0.093	7.037	0.0091
10		0.65	0.096	8.305	0.0094
11		0.26	0.108	4.226	0.0216
12		0.34	0.113	5.929	0.0226
13	18.4	0.44	0.119	7.434	0.0237
14		0.52	0.124	9.238	0.0246
15		0.65	0.127	10.846	0.0254
16		0.26	0.144	4.523	0.0420
17		0.34	0.155	5.995	0.0450
18	26.1	0.44	0.163	8.411	0.0474
19		0.52	0.168	10.780	0.0488
20		0.65	0.171	13.104	0.0498

(PCA) were used to recognize possible correlations between D_c and the studied variables (root diameter, organic matter content, and plasticity index). Moreover, these correlations between soil detachment capacity (dependent variable) and the studied variables (independent variables) were analyzed using a linear multi-regression equation. Finally, observed and predicted values of the soil detachment capacity were compared in a scatterplot. For the determination of model accuracy, the coefficient of determination (R^2), Nash–Sutcliffe efficiency index (NSE), and Root Mean Square Error (RMSE), as common indicators in hydrological studies [53], were used. All statistical analyses were done using the software XLSTAT 9.0, Addinsoft, Paris, France.

Findings

Changes in Soil Properties and Root Diameter

The soil samples under mixed tree species contained roots with a diameter between 0.34 and 0.82 mm with an average value of 0.56 ± 0.15 mm (Table 2). The organic matter content was in the range of 1.39–1.77 %, while its mean was equal to 1.60 %. The mean plasticity index was 21.38 ± 1.78 %, while the lowest and highest values were 18.80 and 24.90 %. (Table 2).

Soil Detachment Capacity

The mean of the five repetitions for each run showed that D_c in the soil samples under mixed tree species was between 0.002 and 0.068 $kg.m^{-2}.s^{-1}$ with an average value of 0.017 ± 0.019 mm (Table 3). It is important to note that there was no significant difference in this hydrological characteristic among experimental sites, which was suitable for the present study.

Pearson's Correlation Matrix and Principal ComponentAnalysis

The results showed that rill detachment capacity (D_c) was negatively correlated with root diameter, organic matter, and plasticity index of soil ($p < 0.01$) (Figure 4). These results were shown in the principal component analysis (PCA) (Figure 5). This analysis revealed two principal components (PC1 and PC2), which explained 84.44% of the total variance of the D_c and the studied

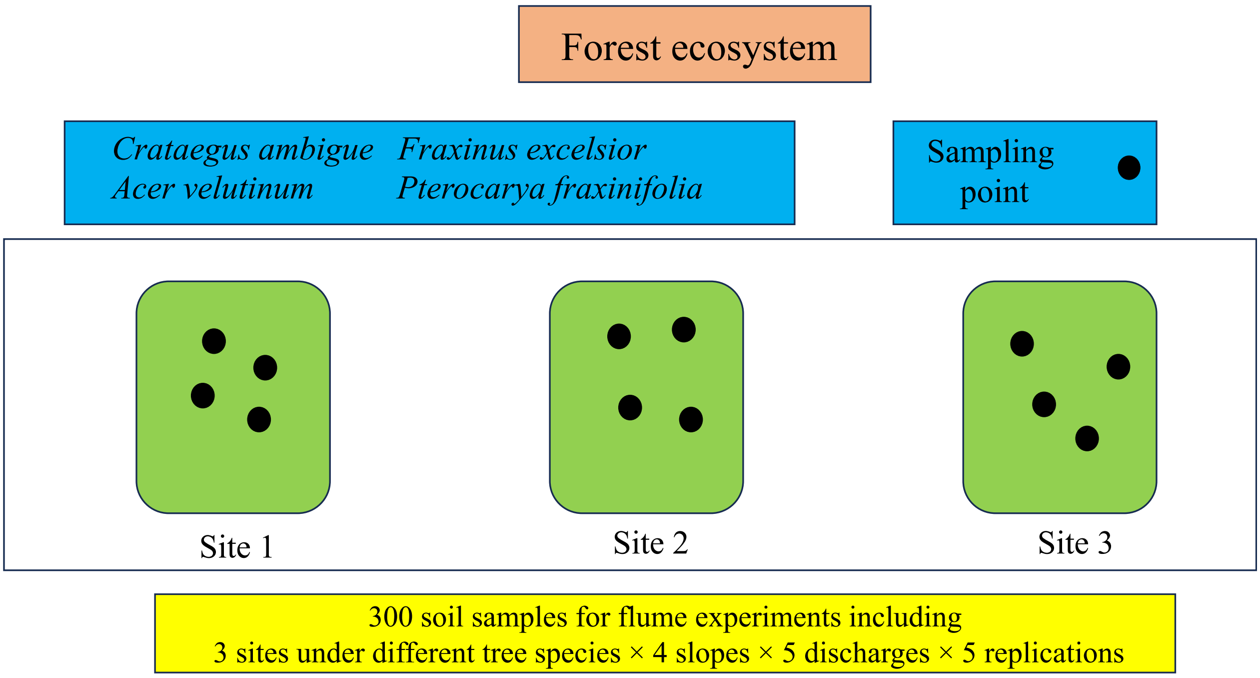

Figure 3) Schematic of experimental design and field sampling.

Table 2) Descriptive statistics of soil properties and root diameter in three experimental sites.

Sites	The studied variables	Mean	Minimum	Maximum	Standard Deviation
Site 1	Root diameter (mm)	0.55	0.34	0.81	0.17
	Organic matter (%)	1.59	1.42	1.67	0.07
	Plasticity index (%)	22.21	18.80	24.90	2.57
Site 2	Root diameter (mm)	0.56	0.41	0.82	0.14
	Organic matter (%)	1.58	1.39	1.76	0.11
	Plasticity index (%)	21.12	18.80	22.68	1.32
Site 3	Root diameter (mm)	0.56	0.34	0.81	0.14
	Organic matter (%)	1.64	1.42	1.77	0.08
	Plasticity index (%)	20.81	18.92	22.68	1.44

Table 3) Descriptive statistics of soil detachment capacity in three experimental sites under the studied species.

Descriptive statistics	Soil detachment capacity (D_c, kg.s^{-1}.m^{-2})		
	Site 1	Site 2	Site 3
Mean	0.021	0.019	0.012
Minimum	0.003	0.003	0.002
Maximum	0.068	0.063	0.052
Standard Deviation	0.022	0.021	0.015

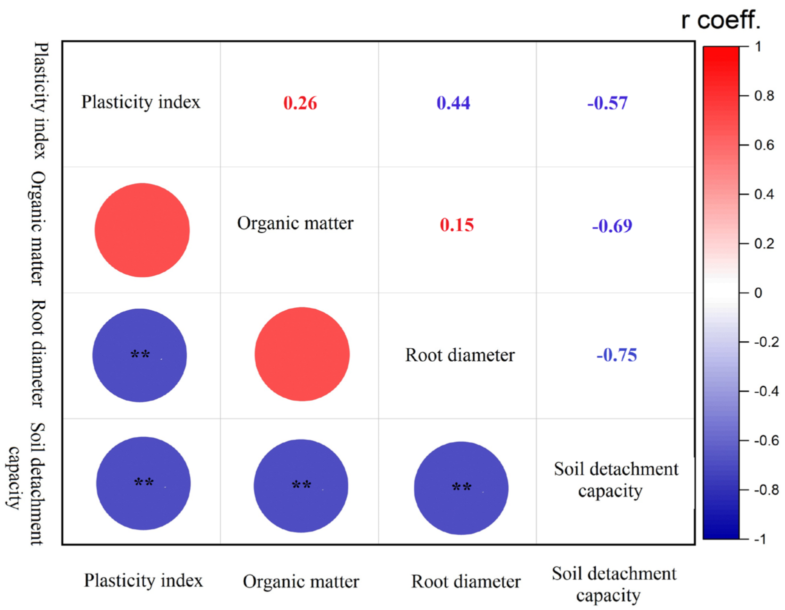

Figure 4) Pearson's correlation matrix of soil detachment capacity and the studied variables (**Note:** ** is significant level at p < 0.01).

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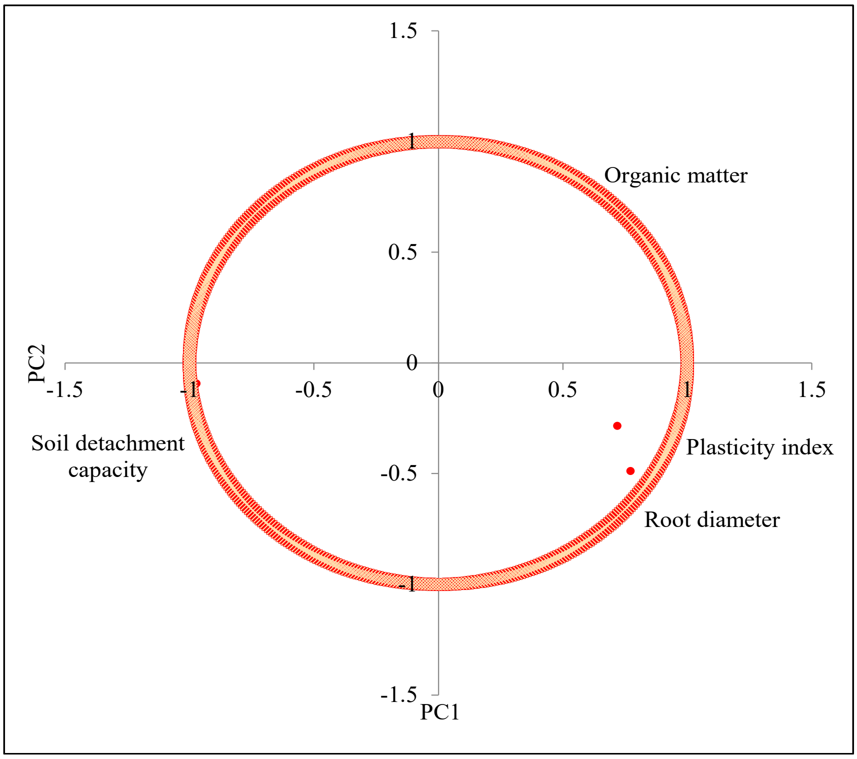

Figure 5) Scores of the original variables (soil detachment capacity, soil properties, and root diameter) on the first principal components measured on soil samples collected under the studied tree species.

variables (including root diameter, organic matter, and plasticity index). In this regard, PC1 and PC2 explained 62.35% and 2.09% of this variability, respectively. Root diameter and plasticity index influenced the first PC (loading over 0.50), and organic matter significantly ($p < 0.01$) influenced PC2 (loading 0.56). D_c was connected with low values of the root diameter, organic matter content, and plasticity index (Table 4 and Figure 5), and this implies that the studied variables have evident and essential effects on rill detachment capacity.

Modeling Soil Detachment Capacity Using Soil Properties and Root Diameter

The proposed model for estimating soil detachment capacity is the following equation Eq. (3):

$$D_c = -0.050\, RD - 0.066\, OM - 0.143\, PI + 0.184 \qquad \text{Eq. (3)}$$

where D_c is soil detachment capacity ($kg.m^{-2}.s^{-1}$), RD is root diameter (mm), OM is organic matter (%), and PI = plasticity index (%).

This equation was very accurate for the simulation of D_c (R^2 equal to 0.92), so the prediction of soil detachment capacity was very close to the line of perfect agreement (Figure 6). Moreover, as reported in Table 5, the indexes of root mean square error (RMSE) and Nash and Sutcliffe (NSE) showed appropriate values for this model.

According to the relationship between the Dc and shear stress, the rill erodibility (as the slope) and critical shear stress (as the intercept) for the studied sites were calculated. The values of these two momentous parameters reflecting soil resistance are presented in Table 6.

Discussion

Relationship Between the Studied Variables and Soil Detachment Capacity

The soils under the studied species showed no significant difference in soil detachment capacity. Sites 1 and 2 had the highest DC

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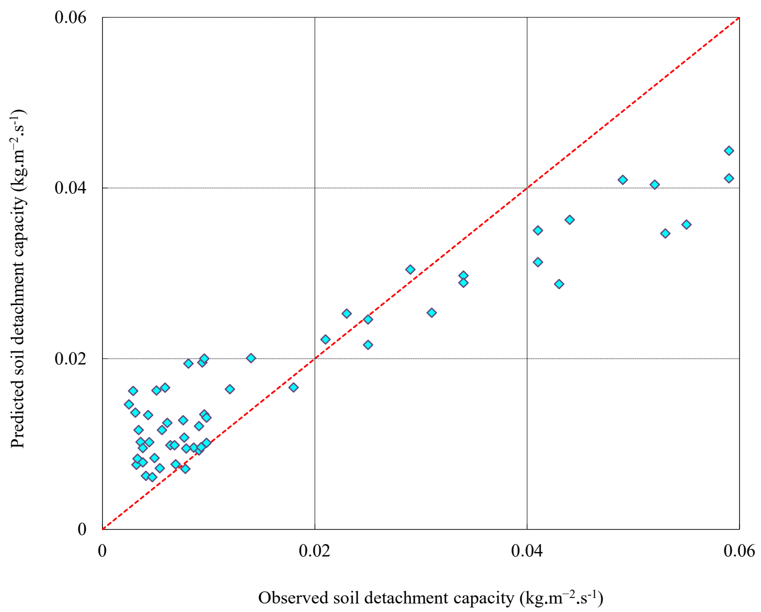

Figure 6) Scatterplots of soil detachment capacity observed and predicted using the multi-regression model according to the studied variables (root diameter, organic matter, and plasticity index) on soil samples collected under the studied tree species.

Table 4) Loadings of the variable studies (soil detachment capacity, soil properties, and root diameter) on Principal Component (PC1) measured on samples collected under the studied tree species.

The Variable Studies	PC_1	PC_2
Soil detachment capacity	**0.943**	0.009
Root diameter	**0.597**	0.238
Organic matter	0.436	**0.556**
Plasticity index	**0.518**	0.081

Note: Significant characteristics at $p < 0.01$ are reported in bold.

and were therefore assumed to be in the worst condition of soil erosion. Comparing the studied sites, in this investigation, organic carbon content had the highest value at site 3 on average by about 1.04 fold. In comparison, the plasticity index had the highest value at site 1 on average by about 1.07 fold. Concerning root diameter, it is not easy to predict the positive effects of this root characteristic on hydrological variables such as soil detachment capacity because there are apparent differences in root diameter among different plant and tree species, resulting in this root effect being considerably different among species. Therefore, further research is needed to reveal the impact of the root diameter of various species on the D_c. As shown in the results, there is no significant difference among the values of root diameter of the selected species, and the average value of this characteristic was 0.56 mm.

The investigated sites (under mixed tree species) had the same soil characteristics, and experimental conditions in the laboratory (such as hydraulic parameters used in the study) were the same for these sites. Therefore, the effects of the studied

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Table 5) Values of the criteria adopted for estimating the precision of the equation obtained from the studied variables, including root diameter, organic matter, and plasticity index.

Hydrological Variable		Descriptive Statistics			
		Minimum	Maximum	Standard Deviation	R^2
Soil Detachment Capacity (D_c, kg.m^{-2}.s^{-1})	Observed	0.068	0.002	0.019	0.92
	Predicted	0.046	0.006	0.011	

Table 6) The relationship between the soil detachment capacity (D_c) and shear stress (t) for the studied sites in forested lands of Guilan Province (the northern part of Iran).

Experimental Conditions	Regression Model	K_r [s.m^{-1}]	τ_c [Pa]	R^2
Site 1	$D_c = 0.0057\tau - 0.0135$	0.0057	2.368	0.54
Site 2	$D_c = 0.0052\tau - 0.0124$	0.0052	2.384	0.52
Site 3	$D_c = 0.0037\tau - 0.0093$	0.0037	2.513	0.51

variables on the soil detachment capacity can be easily understood. When root diameter, soil organic matter, and plasticity index increase, D_c decreases in all sites. Different studies have demonstrated that these three variables had significant effects on D_c. For example, Khanal and Fox [54] reported that the soil erosion rate significantly decreased as root diameter increased. Also, in a previous study, Sedaghatkish et al. [55] found that nonlinear models allow meaningful estimations of the effects of root diameter on soil aggregate stability as an indicator affecting D_c in the studied forestlands. Chen et al. [56] demonstrated a negative correlation of soil rill erodibility (mathematically calculated by the relationship between soil detachment capacity and shear stress) with soil organic matter content. Moreover, based on the results, the soil detachment rate decreases when the plasticity index increases. This result agrees with the study by Khoirullah et al. [37], who reported that soil erodibility decreased with the plasticity index. These authors found that the plasticity index strongly correlated to the erodibility factor.

The correlation and principal components analyses can demonstrate the relationships between the studied variables and soil detachment capacity. In more detail, these statistical techniques have shown that the soil detachment capacity is directly associated with the root diameter, soil organic matter, and plasticity index for the studied tree species. In other words, the results of our analysis identify factors with varying degrees of impact on the soil detachment capacity. Principal components analysis, as a multivariate statistical approach, highlights that when the organic matter content of soil increases, the plasticity index increases, as also shown by PCA. These effects are beneficial since an improved soil structure reduces particle detachment due to the overland flow and, therefore, the soil detachment capacity. Gui [57] found that the liquid and plastic limits (also plasticity index) increase linearly with increased organic matter content. Also, it is demonstrated that plant roots contribute to the formation of stable soil organic matter [58, 59]. Among different characteristics of roots, the diameter of fine roots influences different macroaggregate size classes. Roots with a higher percentage of fine roots (0.2–1 mm) [60] can provide more surface area

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contact with soil particles and contribute to the formation of stable soil macroaggregates enriched with organic carbon [61]. It is important to note that some significant drivers of the mechanical behavior of soils and particle detachment processes have not been explored in this study. For instance, the influence of clay content on soil plasticity has not been adequately analyzed due to the homogenous texture of the experimental soil. Soil cohesion of soils should also be deepened, this physical characteristic being a vital property governing the hydrological and erosive response of soils under plant and tree species.

The Predictive Model for Soil Detachment Capacity by Soil Properties and Root Diameter

The multiple-regression analysis has demonstrated that D_c can be predicted from the studied variables by a robust model with a linear mathematical relationship. The input data of this equation are directly related to the studied variables, i.e., root diameter, soil organic matter, and plasticity index. Therefore, for the hydraulic conditions in this study, the mathematical model predicts the soil detachment capacity. The values of the regression coefficients of the model reveal that the plasticity index has much more influence than the other variables (this coefficient for plasticity index is equal to about 2.86-fold and 2.16-fold the values calculated for the root diameter and soil organic matter, respectively). This result is in line with the findings of Ngezahayo et al. [38], who showed that the plasticity index can be used as one of the input data of the model for predicting erosion rates and has a negative relationship with erosion rate (R^2=0.74). The model coefficients of the studied variables are negative for D_c since the soil detachment capacity decreases when the root diameter, soil organic matter, and plasticity index increase. This regression model, which is based on hydraulic, root system, and soil parameters, is suitable for practical applications since soil slope and water flow discharges are quick to measure in the field. Casagrande's device can easily determine the plasticity index. In contrast, using other soil properties as input parameters for various models requires soil analysis that is not always simple and cheap. However, the proposed model is related to the used and certain experimental conditions. These conditions include concentrated flows, shallow discharge, steep slopes, planted forests, and roots of four tree species. Regression equations must be established for broader equation applications for other experimental conditions. A suggested approach is that the most appropriate values of root diameter, soil organic matter, and plasticity index are needed to keep the modeled D_c under a tolerance limit [62]. Another approach is combining the established model with other soil erosion models. For example, Eq. (3) in this investigation can be used to evaluate the impact of the soil erodibility factor (mathematically modeled by the USLE K-factor) on the annual soil loss [63] through the effect of the soil organic matter on the value of this factor with the same experimental conditions, but various application values of this soil property. It is worth noting that the linear equation proposed in this study is being developed based on data measured in a given environment, where the climatic, morphological, biological, and hydrologic conditions may influence the soil detachment capacity. Also, D_c depends on the overland flow characteristics [64], including shear stress, stream power, unit stream power, and unit energy. Therefore, this equation must be considered site-specific. This means that using these regression models in other environmental conditions must be done cautiously [64] and, in any case, after a proper calibration site by site. Undoubtedly, this simple model is helpful for hydrologists and,

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more in general, land managers, who require reliable estimations of soil detachment rates in environments similar to those of the calibration site.

Conclusions

In this study, we reported the relationships between three variables, including root diameter, soil organic matter, and plasticity index on one side and soil detachment capacity (D_c) on the other side. The study has simulated the D_c on soil samples of four tree species, collected from the top 10 cm of surface soil in forest lands of Northern Iran, using the hydraulic flume at different slopes (6.5, 12.3, 18.4, and 26.1%) and water discharges (0.26, 0.34, 0.44, 0.52, and 0.65 $L.m^{-1}.s^{-1}$). The correlation analysis confirms that when root diameter, soil organic matter, and plasticity index increase, D_c decreases in soils under the studied tree species ($p < 0.01$). The PCA results showed that root diameter and plasticity index influenced the first PC (loading over 0.50), and organic matter significantly influenced PC2 (loading 0.56) ($p < 0.01$). The multiple-regression model, as a function of the studied three variables, can predict D_c accurately and may be helpful for hydrologists and land managers in forest ecosystems. However, there are some limitations in this research. For example, this study has not explored some significant drivers of the mechanical behavior of soils and particle detachment processes. The influence of clay content on soil plasticity has not been adequately analyzed due to the homogenous texture of the experimental soil. The soil cohesion of soils should also be deepened, this physical characteristic being a vital property governing the hydrological and erosive response of soils under plant and tree species.

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