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Effects of rice husk biochar on rill detachment capacity in deforested hillslopes

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Abstract

Biochar addition to soil has been found to be a useful practice to control erosion. However, few studies have explored the effects of biochar produced from husk of rice on rill erosion, due to overland flow in deforested areas. This study has evaluated the rill detachment capacity (D_c) and erodibility (K_r) in soil samples treated with rice husk biochar in comparison to untreated sites (control), collected in deforested hillslopes of Northern Iran. D_c was measured in a lab-scale hydraulic flume at four-bed slopes (9.7, 14.3, 19.5, and 24.2%) and five water discharges (0.24, 0.36, 0.47, 0.59, and 0.69 L m^{-1} s^{-1}). Moreover, organic carbon, aggregate stability and bulk density of soils were measured. D_c was lower (on average -32%) in the treated soil compared to the control. D_c was not correlated to the other physico-chemical properties of soil. K_r, estimated by linear regressions between D_c and shear stress, was noticeably lower (-79%) in the treated soil compared to the control. These results evidence that rice husk biochar is effective at controlling and mitigating soil detachment, and at improving organic matter content and aggregate stability in deforested hillslopes. The proposed values of rill erodibility and shear stress of deforested hillslopes (treated or untreated) are helpful to model soil resistance to rill erosion in process-based erosion models.

Keywords: rill erosion; soil conservation; organic matter content; soil aggregate stability; rill erodibility; shear stress.

1. Introduction

Soil detachment, which is the initial stage of erosion, is the removal of particles from the soil matrix due to raindrop impact or overland flow (Jiang et al. 2020). In the case of clear water, the maximum value of soil detachment in rills formed by erosion is indicated as "rill detachment capacity" (Nearing et al., 1992). This is a key parameter for estimating the rate of soil removed by overland flow (Govers et al., 2007) and describing the overall erosion process (Nearing et al., 1991). Moreover, this parameter is widely used in process-based erosion models, such as the Water Erosion Prediction Project (WEPP) (Wang et al., 2016).

Rill detachment capacity is widely variable, and this variability is due to many factors, such as the soil and plant root characteristics as well as the land use and management (Parhizkar et al., 2021b). The latter factor is essential to reduce the overall erosion rates, since effective soil conservation practices decrease the sediment source for subsequent soil transport and deposition (Zhang et al., 2009). These practices are important in all environments, and essential in deforested areas with high susceptibility to soil erosion (Parhizkar et al., 2020b). For example, some hillslopes that were deforested in recent years in Northern Iran (e.g., Guilan province) have undergone intolerable erosion rates (Parhizkar et al., 2021d), while the previous plant cover prevented noticeable soil loss.

Rill detachment, as other erosion forms, can be noticeably reduced by soil amendment, but with various levels of effectiveness (Li et al., 2021). For instance, supplying soil with biochar, which is produced through pyrolysis of carbon-rich residues in the lack of oxygen (Peng et al., 2011), is a feasible conservation practice that has been successfully used in several environments to mitigate erosion. Theoretically, the biochar has a great capability to improve soil structure, as an organic conditioner (Burrell et al., 2016), since it increases soil carbon thanks to its content in porous organic matter with high stability (Gurwick et al., 2013). Therefore, application of biochar to soil as conservation practice improves soil quality with beneficial effects on its physical, chemical, and microbial properties (Obia et al., 2016; Domene et al., 2014).

Rice, together with corn and wheat, is a common staple food, especially in Asia, where much of the world production is concentrated. Therefore, the vegetal residues of rice yield (such as straw and husk) are abundant at low or zero cost in several Asian countries. Various studies have demonstrated that rice husk is a good substrate to produce biochar, and therefore rice residues can effectively improve soil aggregate stability with consequent reductions in runoff and erosion rates (Jien and Wang, 2013; Gamage et al., 2016). Rice husk biochar can improve the hydrological and other physico-chemical properties of soil, since the cellulosic substances of husk can be incorporated and then degraded (Parhizkar et al., 2020b). As such, rice husk biochar can be practically used for soil conservation in those deforested lands that are prone to soil erosion and degradation, due to the removal of plant cover. It is essential, however, to evaluate how much rice hush biochar is effective and thus beneficial at reducing runoff and erosion rates in deforested lands.

The literature about the impacts of biochar on soil erosion is abundant. For instance, Prakongkep et al. (2021) showed that biochar increases the average size of aggregates and wet aggregate stability by 6 to 25% in comparison to untreated soil in farm fields of Thailand. Ghorbani et al. (2019) reported that the application of biochar significantly increases mean weight diameter (MWD), geometric mean diameter (GMD) and water stable aggregates (WSA) of soil compared to the untreated sites. According to Hseu et al. (2014), during a rainfall event simulated at an intensity of 80 mm h^{-1} on a slope of 20°, erosion significantly decreased by 35% to 90% in soils treated with biochar in comparison to the untreated soil left bare. In Iran, Ahmadi et al. (2020) showed that, in soil with a loamy texture, the application of biochar reduced the runoff coefficient and erosion in comparison to the soil without biochar. These authors also pointed out the need of further studies to obtain a detailed knowledge of the impact of biochar on soil erosion. However, in spite of generally positive experiences, some studies report contrasting effectiveness of biochar at reducing erosion and, more in general, at improving soil quality. For instance, while Nicosia et al. (2021) stated that biochar supplied as soil conditioner increases the storage capacity and prevents soil particle detachment, Zhang et al. (2019) reported that biochar could increase soil erosion, particularly in croplands. Moreover, the investigations focusing the effectiveness of biochar produced from rice husk at reducing the rill erosion are quite scarce, especially on steep slopes in sensitive ecosystems, such as forests or deforested lands (Lucas-Borja et al., 2019a; Parhizkar et al., 2020a; 2021e). Since aggregate stability is a key physical property driving particle detachment, studies investigating its impacts on rill detachment capacity and erodibility in treated vs. untreated soils are needed.

This study: (1) explores the changes in rill detachment capacity of soils treated with rice husk biochar in comparison to untreated sites; (2) analyzes the soil properties that mostly influence rill detachment capacity; and (3) develops regression models to predict rill erodibility from detachment capacity for both treated and untreated soils. The investigation has been carried out using a hydraulic flume that simulated rill detachment at different longitudinal slope and water discharges on soil samples collected in deforested areas of Northern Iran. The results of the study could give land managers insight about the usefulness of treatments with rice husk biochar in deforested lands, where soil conservation is essential, and proposes reliable regression models to predict the magnitude of the rill detachment process, when more precise estimations are not possible or very difficult.

2. Materials and methods

2.1. Study area

A forestland (Saravan Forestland Park) in Guilan province (Northern Iran, 37°08′20″ N; 49°39′42″ E, elevation between 50 and 250 m above the mean sea level) was chosen as case study (Figure 1). The climate of the area, typically Mediterranean, is of Csa type according to the classification by Kottek et al. (2006). On average, the annual temperature is 16.3 °C and the rainfall 1360 mm (IRIMO, 2016). The soil has a silty clay loam texture (sand 12.9%, silt 47.8% and clay 39.3 %) (SDSD, 2017).

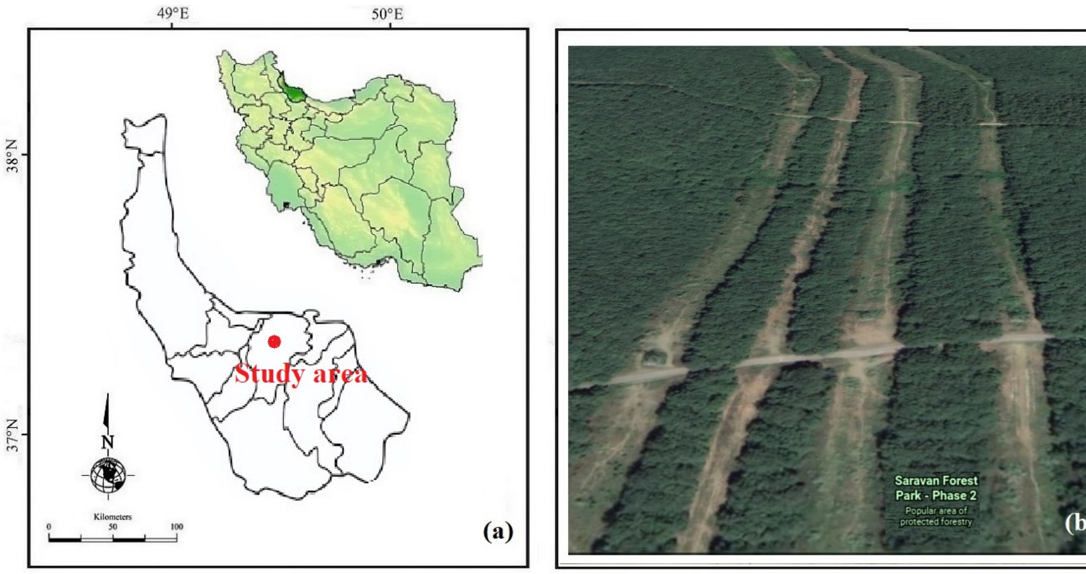


Figure 1 - Geographical location of the study area (a); aerial view (b) of deforested hillslopes (Saravan Forestland Park, Guilan province, Northern Iran) (Source: Google® Map®).

In recent years, Sarawak Forestland Park was deforested and subjected to unsuitable management practices, such as the vegetation removal on hillslopes to install high-voltage power towers (Parhizkar et al., 2020a; 2021b). This resulted in intense soil erosion, particularly in its rill form (Parhizkar et al., 2020c).

2.2. Soil sampling

Between July and August 2021, 20 pairs of soil samples were collected from the uppermost 20 cm in randomly-chosen points of the deforested hillslopes, according to the procedure by Parhizkar et al. (2021b). Of each pair of samples, one was used for both rill detachment simulations in the flume experiments (see section 2.3), and another was subjected to physico-chemical analysis (see section 2.6). Prior to soil sampling, litter and weeds were removed from soil surface. The samples were transported to the Soil Testing Laboratory of the College of Agriculture of Guilan University (Iran).

2.3. Plot preparation

One of each pair of soil samples was placed in an experimental plot with the same size and characteristics of those described by Parhizkar et al. (2020b; 2021b). Two plots were prepared: a first plot received an untreated soil (hereafter indicated as "control" soil); in the other plot, a soil-biochar mixture at 3% (w/w) of biochar was applied ("treated" soil). Biochar was produced from rice husk by an electrical muffle furnace at a peak temperature of 500° C and a duration of 30-45 min for the pyrolysis process, according to the procedure by Ghorbani et al. (2019). Immediately after production, biochar was applied on the plots with treated soils and left there for three months before the experiments by the hydraulic flume (see section 2.5).
Both plots were subjected to wetting and drying cycles in the open air for 24 hours, in order to set the water content of soil at the field capacity. Then, the plots were placed in a room at 25° C throughout a period of 10 months. Finally, small soil samples were extracted from the treated and control plots, using a steel ring (0.1 m in diameter and 0.05 m in height) (Khanal and Fox, 2017; Parhizkar et al., 2021b) for the subsequent flume experiments.

2.4. Flume experiments

The samples extracted from the two plots were subjected to experiments simulating rill detachment in a slope-adjustable hydraulic flume (length × width was 3.5 m × 0.2 m) made of steel. This allowed the measurement of the rill detachment capacity of both treated and control soils at variable flow conditions and longitudinal slopes.
In more detail, each soil sample was inserted in a hole of the flume bed, close to the downstream outlet. Their surface was sprayed with water for 24 h before the experiment, in order to fully saturate the flume bed with water. Then, the flow characteristics were measured according to the procedure setup by Parhizkar et al. (2020a). To summarize, a graduated cylinder was used to measure the water discharge at the downstream outlet of the flume in six replications. The surface flow velocity of the water stream was determined in nine replications using the fluorescent dye technique. The mean velocity was calculated after correction using the coefficients propose by

Abrahams et al. (1985). A level probe and a self-made digital instrument with accuracy of 1 mm (Parhizkar et al., 2021c) were used to measure the mean water depth, averaging six measurements in two cross-sections and three points per section (Parhizkar et al., 2020a). The experiment ended when the depth of the eroded soil in the steel ring was approximately 0.015 m or after five minutes from the experiment start. The weight of scoured sediments in each experiment was determined after soil drying in oven for 24 h at 105 °C. Further details about the flume characteristics and the experiments are reported in Parhizkar et al. (2020a; 2021a).

2.5. Experimental design

Twenty combinations of four slopes of the flume bed (9.7%, 14.3%, 19.5%, and 24.2%) and five water discharges (0.24, 0.36, 0.47, 0.59, and 0.69 L m^{-1} s^{-1}) were setup for each soil sample (Table 1). The values of bed slope were selected according to the longitudinal gradient of the natural hillslopes in the study area, while the water discharges were chosen from field measurements of overland flows (Parhizkar et al., 2020a; 2021b). Each experiment was conducted in five replicates. Therefore, the experimental designed consisted of 200 flume experiments: two soil conditions (treated vs. control) × four bed slopes × five water discharges × five replications.

2.6. Calculation of rill detachment capacity, erodibility and shear stress

The mean rill detachment capacity (D_c, kg s^{-1} m^{-2}), under each combination of bed slope and water discharge, was calculated by equation (1):

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

where ΔM is the dry weight of detached soil (kg), A is the area of the soil sample (m^2), Δt is the experiment duration (s) and α the slope angle of the flume bed (°).

Rill erodibility (K_r, s m^{-1}) and critical shear stress (τ_c, Pa) are meaningful indicators of the soil resistance to rill erosion (Wang et al., 2014), commonly used in hydrological models, such as the WEPP model (Nearing et al., 1989). These parameters were estimated as the slope and intercept of the following equation, which linearly interpolates D_c and shear stress (τ):

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

The shear stress, according to Nearing et al. (1997), was estimated using the following equation (3):

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

where ρ is the 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}).

Table 1 - Values of the hydraulic parameters in the flume experiments for measuring the rill detachment capacity on samples collected in deforested hillslopes of Guilan province (Northern Iran) and treated with rice husk biochar or left undisturbed (control).

Slope (S, %)	**Water discharge (q, L m^{-1} s^{-1})**	**Water depth (h, cm)**	**Hydraulic radius (R, m)**	**Shear stress (τ, Pa)**
9.7	0.24	0.560	0.005	5.041
	0.36	0.680	0.006	6.053
	0.47	0.790	0.007	6.960
	0.59	0.880	0.008	7.689
	0.69	0.956	0.009	8.295
14.3	0.24	0.466	0.004	6.201
	0.36	0.577	0.005	7.645
	0.47	0.694	0.006	9.095
	0.59	0.781	0.007	10.152
	0.69	0.881	0.008	11.347
19.5	0.24	0.342	0.003	6.319
	0.36	0.427	0.004	7.826
	0.47	0.571	0.005	10.322
	0.59	0.681	0.006	12.184
	0.69	0.772	0.007	13.696
24.2	0.24	0.291	0.003	6.706
	0.36	0.364	0.004	8.329
	0.47	0.485	0.005	10.970
	0.59	0.583	0.006	13.065
	0.69	0.676	0.006	15.017

2.7. Soil analysis

Each soil sample extracted for physico-chemical analysis was air-dried and sieved through a 2-mm mesh. The following physico-chemical properties were measured: (1) organic carbon (OC, using the Walkley - Black technique, Allison, 1975); (2) medium weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregates as well as water stable aggregate (Kemper and Rosenau, 1986; Kandeler, 1996), by the wet sieving method; and (3) bulk density (BD), using the clod method (Radcliffe and Simunek, 2010).

2.8. Statistical analysis

A paired sample t-test was used to identify statistically significant differences in rill detachment capacity between control and treated soils at p-level < 0.01. QQ-plots were used to check the normality of sample distribution.

A Principal Component Analysis (PCA) was applied to identify possible associations among rill detachment capacity and physico-chemical properties of the treated and control soils.

Finally, a linear regression analysis was carried out to study the relationships between the rill detachment capacity and the shear stress.

The statistical analyses were performed using XLSTAT 9.0 software (Addinsoft, Paris, France).

3. Results

3.1. Variations of rill detachment capacity and soil physico-chemical properties between treated and control soils

The rill detachment capacity (D_c) in the control soil was significantly (p < 0.01) higher compared to the treated plot. Soil treatment with rice husk biochar decreased D_c by 32.5% (0.046 ± 0.024 kg m^{-2} s^{-1} against a value 0.031± 0.014 kg m^{-2} s^{-1} measured for the control soil). The latter soil condition showed a lower variability in D_c, shown by the lower standard deviation compared to the control (Figure 2).

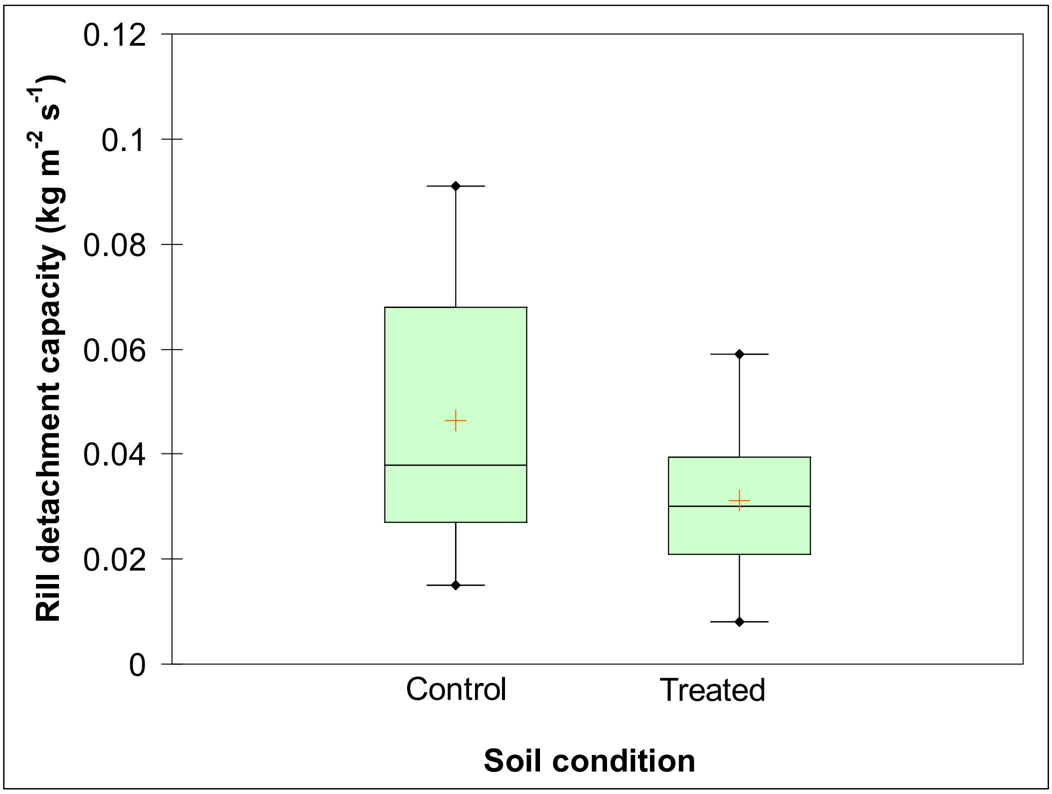


Figure 2 - Box plots of rill detachment capacity measured using flume experiments on samples collected in deforested hillslopes of Guilan province (Northern Iran) and treated with rice husk biochar or left undisturbed (control).

All soil properties were significantly different between the treated and control plots ($p < 0.01$). In comparison to the control, the treated soil showed an average increase in OC by 21.2%, while MWD, WSA and GMD increased on average by 47.8%, 20.9% and 23.7%, respectively. In contrast, the BD of the treated soil was lower by 10% compared to the control (Table 2).

Table 2 - Values of the main soil properties (mean ± std. dev.) measured in samples (n = 20) collected in deforested hillslopes of Guilan province (Northern Iran) and treated with rice husk biochar or left undisturbed (control).

Soil properties	Soil condition	
	Treated	**Control**
OC (%)	2.15 ± 0.28 a	1.77 ± 0.08 b
MWD (mm)	0.98 ± 0.15 a	0.66 ± 0.08 b
WSA (%)	45.38 ± 4.44 a	37.55 ± 3.89 b
GMD (mm)	0.64 ± 0.11 a	0.52 ± 0.06 b
BD (kg m^{-3})	1411 ± 45.27 a	1568 ± 23.83 b

Notes: OC = organic carbon; MWD = medium weight diameter of soil aggregates; WSA = water stable aggregate; GMD = geometric mean diameter of soil aggregates; BD = bulk density. Different letters in each line indicate significant differences ($p < 0.01$, Tukey test) between control and treated soils.

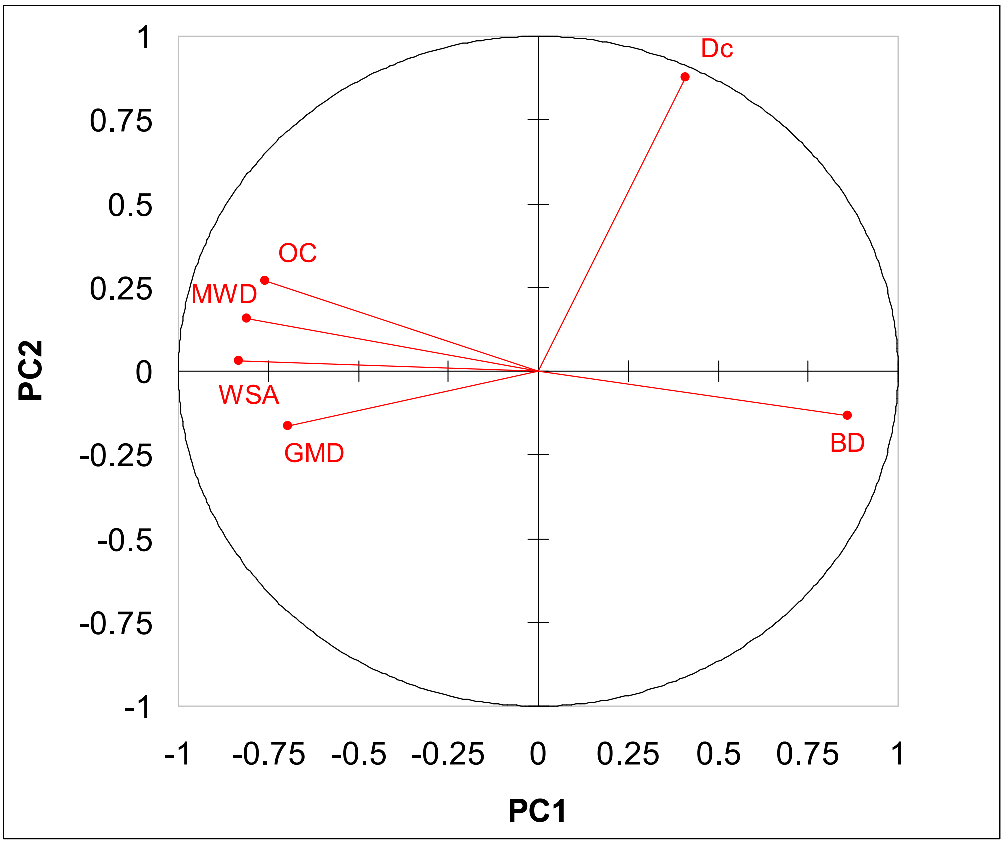
The PCA identified two principal components (PC1 and PC2), which explained together 70.4% of the total variance of the original variables (rill detachment capacity and physico-chemical properties of soils). More specifically, PC1 and PC2 depicted 55.19% and 15.17% of this variability, respectively. All the physico-chemical properties of soil influenced the first PC (loadings > 0.483), while the rill detachment capacity heavily weighted in the PC2 (loading of 0.767). In other words, the PC1 increased with OC, BD, MWD, WSA and GMD, while the second PC increased only with D_c (Table 3 and Figure 3a). This means that the analyzed physico-chemical properties did not influence D_c, since the two PCs are uncorrelated.

A clear gradient along the first PC was found between treated and control soils, when the scores of the soil samples were plotted on the first two PCs. Two well-discriminated clusters, one for each soil condition, were evident, which discriminated soils treated with rice husk biochar from untreated soils (Figure 3b).

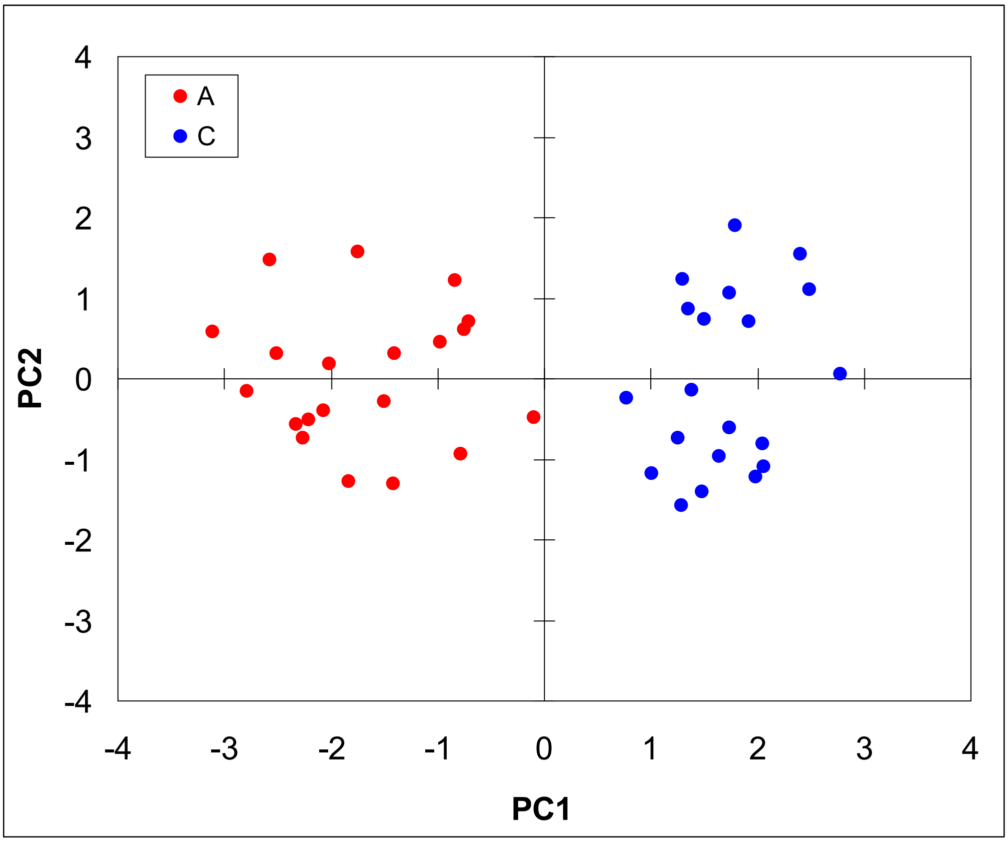
Table 3 - Loadings of the original variables (rill detachment capacity and soil physico-chemical properties) on the first Principal Components (PC1 and PC2) measured on samples collected in deforested hillslopes of Guilan province (Northern Iran) and treated with rice husk biochar or left undisturbed (control).

Original variables	PC_1	PC_2
D_c	0.168	**0.767**
OC	**0.576**	0.072
BD	**0.738**	0.018
MWD	**0.658**	0.025
WSA	**0.690**	0.001
GMD	**0.483**	0.027

Notes: D_C = rill detachment capacity; OC = organic carbon; BD = bulk density; MWD = medium weight diameter of soil aggregates; WSA = water stable aggregate; GMD = Geometric mean diameter of soil aggregates. Significant parameters at $p < 0.01$ are reported in bold.


Dc
OC
MWD
WSA
GMD
BD
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
PC2
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
PC1

(a)


A
C
4
3
2
1
0
-1
-2
-3
-4
PC2
-4
-3
-2
-1
0
1
2
3
4
PC1

(b)

Legend: D_C = rill detachment capacity; OC = organic carbon; BD = bulk density; MWD = medium weight diameter of soil aggregates; WSA = water stable aggregate; GMD = Geometric mean diameter of soil aggregates.

Figure 3 - Loadings of rill detachment capacity and soil physico-chemical properties (a), and scores (b) of the original variables (rill detachment capacity and soil properties) on the first Principal Components (PC1 and PC2) measured on samples collected in deforested hillslopes of Guilan province (Northern Iran) and treated with rice husk biochar (A) or left undisturbed (control, C).

3.2. Estimation of rill erodibility using linear regression equations

The linear regression models that interpolate D_c and τ by equation (2) showed high coefficients of determination (0.92 and 0.88 for control and treated soil, respectively, $p < 0.01$) (Figure 4), and this highlights the strong influence of the shear stress on the rill detachment process. The slope (K_r) and intercept (τ_c) were different between the two soil conditions, as expected. In more detail, both K_r and τ_c were lower in the treated soils (0.0047 s m^{-1} and 2.51 Pa, respectively) compared to the control (0.0081 s m^{-1} and 3.46 Pa) (Figure 4).

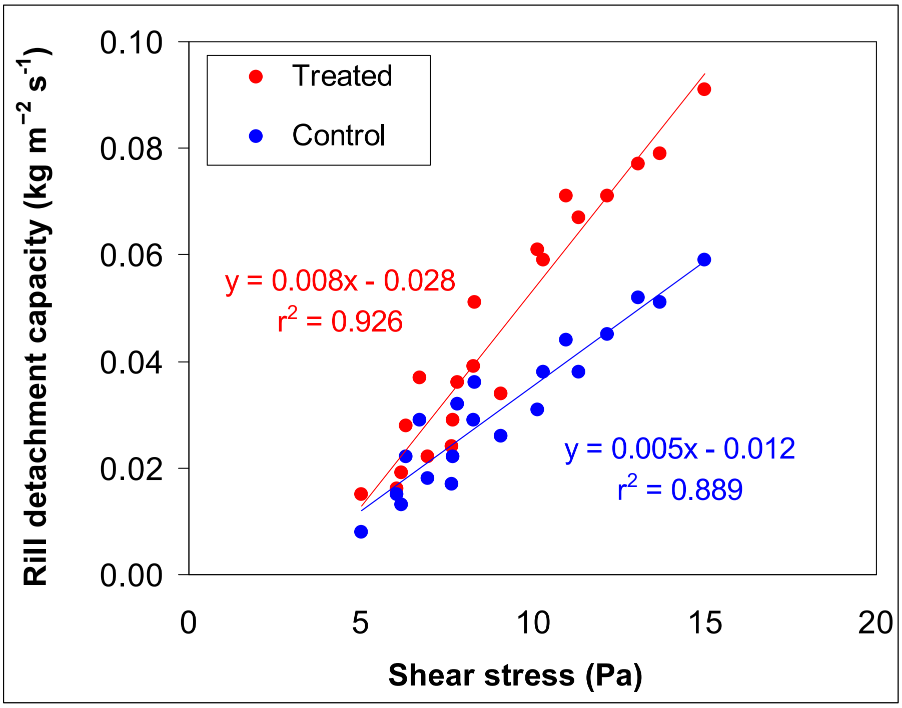


Figure 4 – Linear regression equations between the rill detachment capacity ($y = D_c$) and shear stress ($x = \tau$) estimated on soil samples collected in deforested hillslopes of Guilan province (Northern Iran) and treated with rice husk biochar or left undisturbed (control).

4. Discussions

4.1. Influence of biochar on soil properties and rill detachment capacity

The soils of the study area (treated with rice husk biochar and untreated), of similar type and texture, were subjected to rill detachment simulations under the same experimental conditions. Hence, the impacts of the treatment on the rill detachment capacity and erodibility can be easily identified.

The analysis of the main physico-chemical properties of soils carried out in this investigation confirms the higher quality of treated soils as well as more resistance to rill detachment compared to the control plots. In contrast, the latter soils (simulating the deforested and untreated sites) showed higher degradation and erodibility.

The significant increase in organic carbon content of the treated soil compared to the untreated soil is consistent with the findings of other authors (e.g., Masulili et al., 2010; Ghorbani et al., 2019). The increased organic carbon content indicates beneficial conditions for cultivation of the investigated soils (Gamage et al., 2016), since a higher organic matter content (linked to the organic carbon) improves soil fertility and thus enhances crop growth and yield. Biochar plays a significant effect on soil organic carbon, since this substrate contains fresh organic matter (Dume et al., 2016). Moreover, some investigations report that biochar, due to its stable structure, is resistant to surface oxidation of organic carbon, and therefore this soil conditioner is effective at improving the agronomic conditions of the soil (Nguyen et al., 2008).

The significant differences in the indices of soil aggregate stability observed in this study for the treated soil may be due to the organic matter supply, as observed by Zeraatpisheh et al. (2021). These authors showed that soil organic matter has a very high influence on aggregate stability indices. This increase is beneficial for soil aggregation, since the organic compounds act as cement for soil particles. In general, soil disturbance due to anthropogenic factors (e.g., land abandonment, deforestation, cultivation) result in decreases in soil organic matter and thus aggregate stability (Lucas-Borja et al., 2019b; Shabanpour et al., 2020). According to Li et al. (1992), high aggregate stability results in high resistance to rill erosion of soil due to the overland flow.

The lower bulk density measured in the treated soil may be attributed to the increase in the volume of the soil-biochar mixture over time (Ghorbani et al., 2019). In other words, the rearrangement of soil and biochar particles, which is due to the release of applied pressure by soil-organic complex, could have reduced the bulk density in soils treated with biochar (Pandian et al., 2016). This result also agrees with the findings of other authors (e.g., Herath et al., 2013; Jien and Wang, 2013), who reported that the total porosity and macroporosity of soils significantly increase when organic soil conditioners, such as biochar, are added.

Rill detachment variability was in the same direction as the changes in soil physico-chemical properties. The decrease in soil erodibility thanks to treatment with rice hush biochar can be considered as a beneficial effect against soil degradation in forestland. This decrease is consistent with the statements of Jien and Wang (2013). These authors report that biochar is able to improve the physical and chemical properties of degraded soil, and reduce erosion, because its application increases macro-aggregates and help in mitigating erosion. In contrast, biochar may not be an appropriate material for all conditions, such it could enhance the loss of humus in forestland (Wardle et al., 2008) and increase the displacement of the biochar particles on the soil surface (Verheijen et al. 2009).

As highlighted by the principal component analysis, the two soil conditions (soils treated with rice husk biochar and untreated sites) are clearly different in terms of rill detachment capacity, organic carbon, and aggregate stability. However, the PCA did not associate the variability in rill detachment capacity with organic carbon, aggregate stability, and bulk density. This contrasts the findings of Parhizkar et al. (2020a), who report that an increase in organic carbon and aggregate stability implies a decrease in rill detachment capacity, and the opposite happens for bulk density. That investigation was carried out in undisturbed woodlands and forestlands. In our study, the management operations carried out in recent years in the experimental hillslopes may have altered the soil surface, which may explains the inconsistency between the results of this study and those by Parhizkar et al. (2020a). Other studies report negative correlations between the indices related to the soil aggregate stability, and the detachment capacity (e.g., De Baets et al., 2006; Wang et al., 2018). Moreover, the soil samples collected under the two conditions (treated and untreated plots) are clustered in two well-discriminated groups, and this may be a result of the differences in the analyzed soil properties (organic matter, aggregate stability, bulk density and rill detachment). This means that the changes in these properties due to biochar addition to soil may alter the soil erodibility. It is noteworthy that the distinction between untreated soils and sites supplied with substrates that are rich in organic matter (such the rice husk biochar) is consistent with the differences in soil erodibility and quality found between bare and hydromulched soils in a previous study carried out in the same environment (Parhizkar et al., 2021b).

4.2. Influence of rice husk biochar on rill erodibility

This study has demonstrated that the soil treatment with biochar is able to reduce rill erodibility. For the untreated soil, this parameter was about two-fold the value measured in the treated soil. This result is in accordance with Seitz et al. (2020), who found that the soil erodibility decreases in sandy and silty soils with biochar addition. Moreover, Li et al. (2021) showed that biochar successfully decreases flow turbulence on rills formed by erosion and thus reduces the sediment transport rate on hillslopes. Overall, the soil conservation practices based on treatment with biochar can increase the water storage capacity of soil and prevent soil particle detachment (Nicosia et al., 2021). In contrast, biochar addition could increase soil erosion, especially in cultivated lands (Zhang et al., 2019).

In this investigation, the linear regression model based on the interpolation between rill detachment capacity and shear stress is very accurate, as shown by the high coefficients of determination calculated for the two soil conditions. This result agrees with the results of the previous works of Parhizkar et al. (2020a; 2020b; 2020c; 2021b) in the same study area, and Zhang et al. (2008). These studies also report very high coefficients of determination for equations established between the rill detachment capacity and shear stress under different experimental conditions.

It is important to highlight that the soil erodibility estimated for the soil treated with rice husk biochar is higher compared to the values measured for hydromulched soils in the previous work by Parhizkar et al. (2021b). This can be due to the beneficial effects of hydromulch roots on soil properties, which exert a noticeable reduction in rill erodibility. These beneficial effects are in accordance with the outcomes of Mamo and Bubenzer (2001), who report that the presence of living plant roots supports the reduction in rill detachment capacity and erodibility of soils. However, the hydrological effects of soil treatment with biochar develop more quickly compared to grass growth in the hydromulched sites, and this characteristic may be appreciated in emergency actions for soil conservation.

Overall, the results of this study show that the reduced values of rill erodibility in sites treated with rice husk biochar in comparison to the untreated soils may be of interest for land planners, in order to implement suitable soil conservation programs to reduce the soil erosion risks. Actually, the rill erodibility, as being the slope of the equation interpolating rill detachment capacity and shear stress, is a measure of the soil resistance to rill erosion (Nearing et al., 1992). Therefore, the precise estimation of rill erodibility is necessary to implement effective soil conservation actions.

5. Conclusions

In the case study of deforested hillslopes of Northern Iran, rill detachment capacity in soil treated with rice husk biochar was significantly lower compared to the untreated sites. In contrast, the organic carbon and aggregate stability of soils were significantly higher and the bulk density was lower. Rill detachment capacity was not correlated to the other physico-chemical properties of soil. Rill erodibility of deforested hillslopes, calculated by linear regressions between rill detachment capacity and shear stress, was markedly lower in the treated soil compared to the untreated sites. These findings highlight the effectiveness of the rice husk biochar to control and mitigate soil detachment and improve organic matter content and aggregate stability in deforested hillslopes. Moreover, the proposed values of rill erodibility and shear stress for deforested hillslopes (treated or not) are helpful for both hydrologists (who must reproduce soil resistance to rill erosion in process-based erosion models) and land planners (who must setup the most effective soil conservation actions) working in delicate ecosystems, such as deforested lands that are exposed to intense erosion.

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