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Changes in rill detachment capacity after deforestation and soil conservation practices in forestlands of Northern Iran

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Abstract

Rill erosion is particularly intense after deforestation on hillslopes with steep and long profiles. Since the rill detachment capacity ("D_c") shows a noticeable variability resulting from different soil properties and vegetation characteristics, there is a need to explore the changes in key soil properties and rill erosion rates under different natural or planted species and a variety of soil conservation practices after deforestation. This study evaluates the changes in four key soil properties (organic carbon content, bulk density and water-stable aggregates of soil, and weight density of plant roots) and rill detachment capacity in forest sites with natural tree species as well as in areas subjected to reforestation and soil conservation treatments in comparison to deforested sites. To this aim, 2000 soil samples have been collected in forestlands of Northern Iran. Sampling was done in deforested areas (assumed as reference condition), and in forest sites 14 plant species (natural or after reforestation). Deforested samples were subjected to five soil conservation treatments (using additives or hydromulching). On all soil samples, D_c has been measured in a laboratory flume at five water flow rates (0.27 to 0.69 $L\ m^{-1}\ s^{-1}$) and five soil slopes (5.9 to 31.7%). All soil properties, when compared to the reference condition, were significantly different (between -50% to 124%) among the three soil conditions (natural forests, reforested soils and deforested and treated sites), the natural forests and the treated sites showing a better quality compared to planted forests. D_c was noticeably lower in all conditions (0.022 ± 0.021 $kg\ m^{-2}\ s^{-1}$) compared to the deforested and untreated sites (0.046 ± 0.023 $kg\ m^{-2}\ s^{-1}$) . Natural and planted forests showed a similar decrease in rill erodibility (-70 to 80%), while a much lower reduction in D_c (-36%) was measured for the treated areas. Overall, the study demonstrates that the changes in soil properties due to plant species and soil management as well as the associated variability in rill detachment are noticeably site-specific, and greatly depend on soil conservation treatments. The results of this study may give landscape planners clear indications about the relationships between rill detachment and the associated soil properties among treated and untreated (natural or reforested) soils.

Keywords: soil organic carbon; soil bulk density; root weight density; aggregate stability; rill erodibility.

1. Introduction

Deforestation, due to natural or anthropogenic factors (such as fire and logging), leads to severe degradation in forest ecosystems (van Lierop et al., 2015; Watson et al., 2018) such as increased surface runoff and soil erosion. The latter process depends on the detachment of particles in the soil left bare from vegetation, due to rainsplash and overland flow (Cantón et al., 2011; Polyakov and Nearing, 2003). Overland flow forms rills with increasing depth and width downstream (Ellison, 1947; Li et al., 2019; Wang et al., 2014), especially on steep and long slopes (Owoputi and Stolte, 1995; Wang et al., 2014). The control of the maximum value of the rill detachment rate (the so-called “rill detachment capacity”, hereafter indicated as “D_c”) in deforested sites is essential to reduce rill formation. This allows the mitigation of the overall erosion in areas that can be sources of huge amounts of sediments and thus may damage infrastructures downstream of eroded forests (Cantón et al., 2011; Gyssels et al., 2005).

Rill erosion shows a noticeable variability in soils supporting different vegetation species (natural or planted for reforestation purposes), and this depends on morphological, hydraulic and physico-chemical properties of soil as well as characteristics of the vegetal root system (McGuire et al., 2013; Polyakov and Nearing, 2003). Eminent literature has confirmed the influence of these variables on soil detachment (e.g., Li et al., 2015; Parhizkar et al., 2020a; Wang et al., 2018). For instance, the variability of D_c with hydraulic characteristics of flow was explored by (Parhizkar et al., 2021c; Wang et al., 2016), while (Parhizkar et al., 2021d; Wang et al., 2014) studied the response of D_c to changes in soil and plant root characteristics.

In addition to the variability in the rill detachment rates in sites with different vegetal species, the application of soil conservation practices can increase the complexity of rill erosion processes, which become very difficult to be controlled and predicted (van Lierop et al., 2015). In other words, spreading additives of natural or synthetic origin (e.g., mulch, organic compounds, microbial substrates, bioplastics) increases the biochemical activities and organic matter content of treated soils (Barreiro et al., 2010; Cerdà et al., 2016; Prosdocimi et al., 2016). The changes in the soil and plant root characteristics resulting in modifications in soil erodibility sum up the natural variability of soil resistance to erosion (Abdi et al., 2019; Baets et al., 2007; Zhang et al., 2013).

Ample and eminent literature has explored the effects of vegetation species and soil conservation practices on both soil properties and erosion processes also in deforested areas (e.g., Meena et al., 2020; Torri et al., 1995; Wang et al., 2014). However, the reciprocal associations among the changes in soil parameters on one side, and rill detachment capacity on the other side are not always reported in the relevant studies on a quantitative basis. Moreover, the investigations have been carried out using different methods (e.g., rainfall simulations, monitoring in plots, flume experiments) and on different scales (e.g., from microplots to hillslopes), making an objective evaluation of the rill detachment rates quite hard, when impossible, under different conditions. There is the need to compare the D_c changes among soils with given vegetal species or subjected to a specific conservation practice as well as to explore whether and to what extent these changes can be associated to the changes in key soil parameters. This comparison must be made under standardised hydraulic and morphological conditions, in order to give forest managers clear indications about the effectiveness of each soil conservation technique as well as the rill detachment process in natural or planted areas. This may provide technicians with insights about prioritisation of actions in the case that the rill erosion exceeds the tolerable rates. Unfortunately, to the authors' knowledge, no studies have compared D_c and the associated changes in soil and plant root characteristics under comparable conditions and among a large variety of plant species and soil conservation techniques.

To fill this gap, this study has evaluated the changes in four key soil properties (root weight density, and organic carbon content, bulk density and water-stable aggregates of soil) and rill detachment capacity in forest sites with natural tree species as well as in areas subjected to reforestation and soil conservation treatments in comparison to deforested sites. To this aim, 250 soil samples have been collected in the forestlands of Northern Iran. D_c has been measured on soil samples collected in deforested, natural and reforested areas (supporting 14 native or non-native species) and sites subjected to five soil treatments at variable water flow rates and soil slopes in a laboratory flume. The specific objectives of the study are the following: (i) to measure the variability in D_c and those soil properties and plant root characteristics among natural, reforested and managed soils compared to deforested sites; (ii) to explore the possible associations among the studied variables based on a correlation analysis; and (iii) to understand whether rill detachment and the other soil and root properties are discriminated among the natural conditions of forests, reforestation and soil conservation practices, adopting multivariate statistical techniques.

2. Materials and methods

2.1. Study areas

Two forest parks (Saravan and Saqalaksar Parks, geographical coordinates 37°08′04″ N, 49°39′44″ E, and 37°09'23.98" N, 49°31'49.48" E) were identified as study areas, close to Rasht city (Guilan province, Northern Iran) at an elevation between 50 and 205 m above the mean sea level (Figure 1). The climate of the study areas is “Csa” type (Köppen-Geiger classification, (Kottek et al., 2006). Winter is warm and wet, while summer is very hot and dry, as in typical Mediterranean conditions. The mean annual values of rainfall and temperature are equal to 1360 mm and 16.3 °C, respectively (Iran Meteorological Organization, data of 2016).

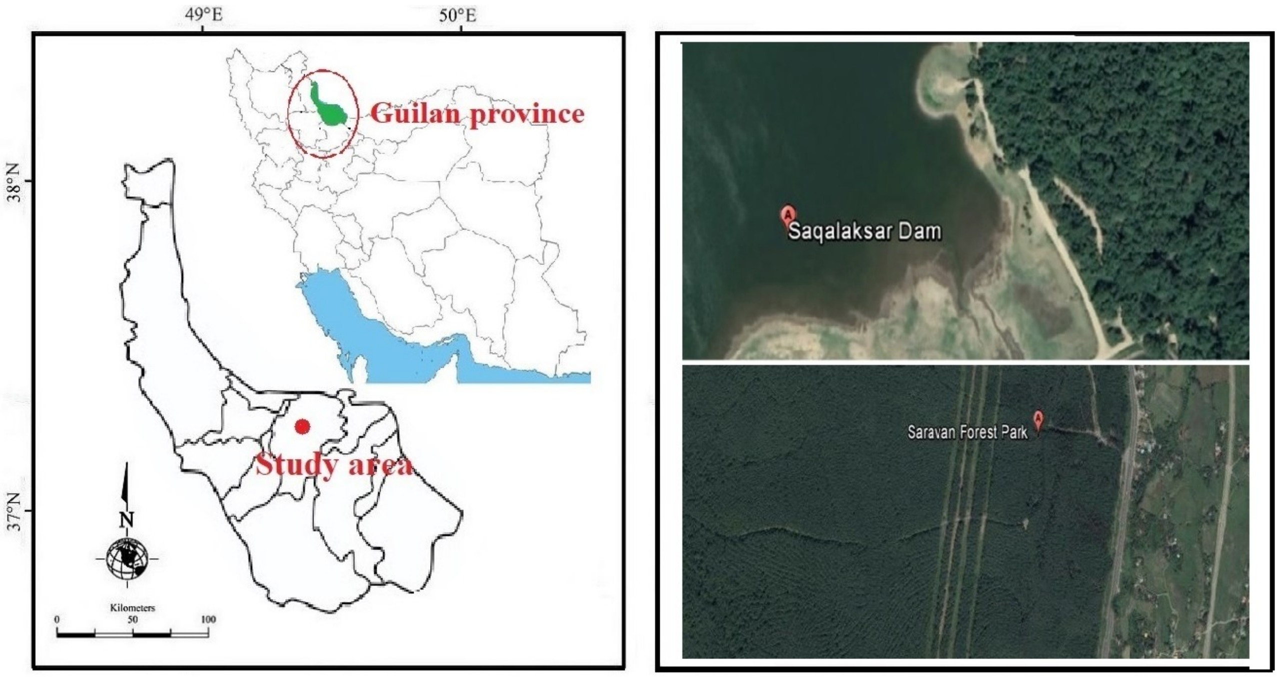


Figure 1 - Geographical location (left) and orthophotos (right) of the two study areas (Saravan and Saqalaksar Forestland Parks, Northern Iran).

Both areas show a dense vegetation cover and a large variety of tree and plant species before deforestation (Figure 2a). The main tree species in Saqalaksar Park are *Zelkova carpinifolia* (hereinafter indicated as “Zc”), *Quercus castaneifolia* (Qc), *Alnus glutinosa* (Ag), *Parrotia persica* (Pp), *Pinus taeda* (Pt), and *Carpinus betulus* (Cb). In Saravan Park, vegetation mainly consists of

Alnus subcordata (As), *Brachythecium plumose* (Bp), *Gleditsia caspica* (Gc), *Sambucus ebulus* (Se), *Oriental beech* (Ob), *Crataegus ambigue* (Ca), *Rubus persicus* (Rp) and *Primula heterochroma* (Ph).

In the past two decades, the parks have been intensely deforested for the installation of high-voltage power towers (Figure 2a). This deforestation led to intense interrill and rill erosion (the latter more severe on steep slopes) (Figure 2b). Scientific evidence and quantification of this erosion and subsequent degradation of deforested soil can be found in the works by Sedaghatkish et al. (2023), and Parhizkar et al. (2020b, 2021a). To limit the undesired impacts, deforested forestlands were partly restored by planting young trees of *Zelkova carpinifolia*, *Quercus castaneifolia* and *Alnus glutinosa*.

(a)

(a)

(b)

Figure 2 - Deforested lands (a, Saravan Forestland Park), and evidences of intense rill erosion (b, Saqalaksar Forestland Park) in the two study areas (Guilan Province, Northern Iran).

Soils of both parks are quite homogenous, with silty clay loamy texture for both sites (on average 20% of sand, 47% of silt and 33% of clay in Saqalaksar Park, and 13% of sand, 50% of silt and 37% of clay in Saravan Park). Both soils are Cutanic Luvisols (WRB classification)/Ultic Hapludalfs (USDA Soil Taxonomy).

2.2. Experimental design

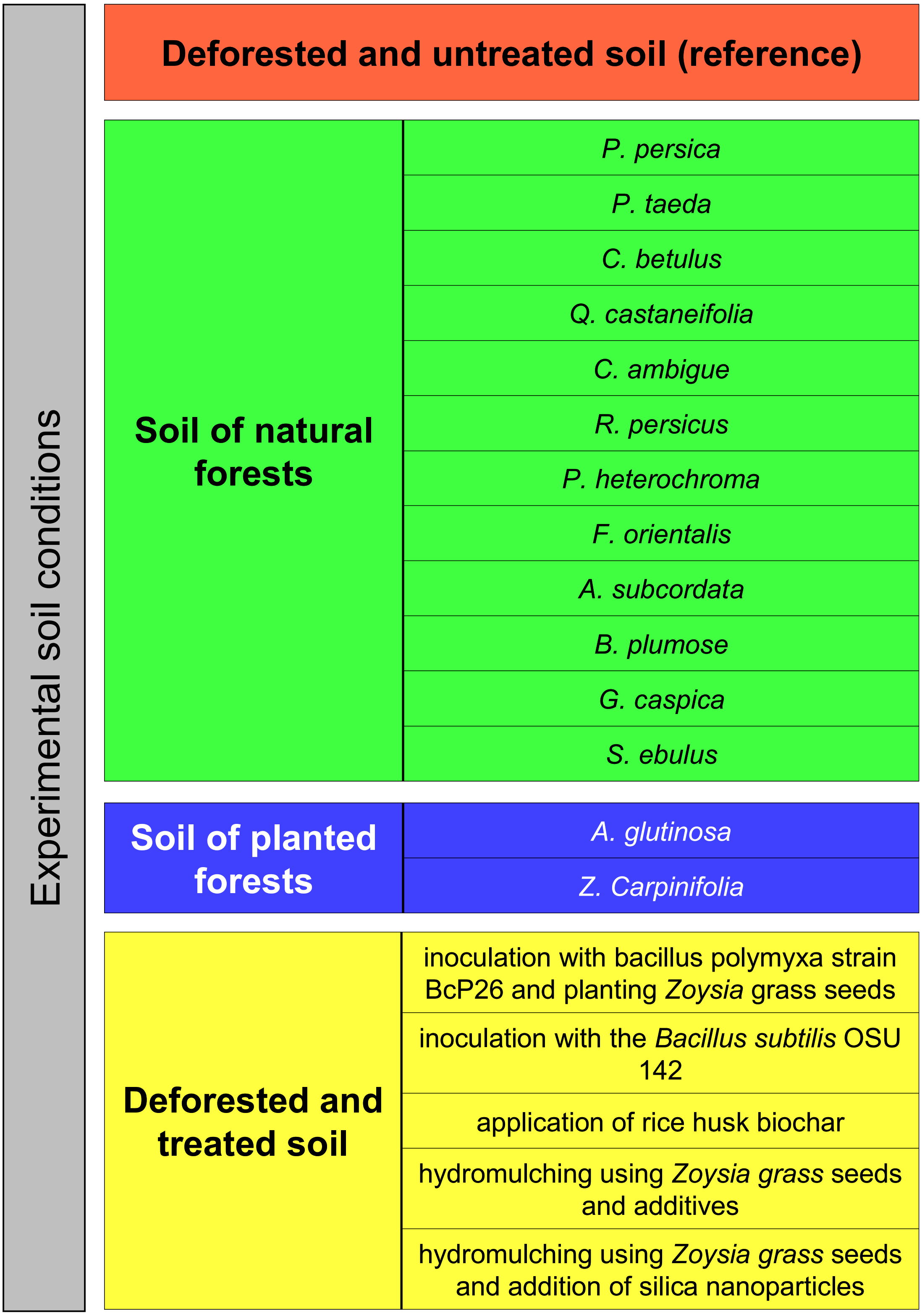
The following soil conditions were simulated in as many experimental plots (see sections 2.3 and 2.4) to analyse the related changes in the soil properties and D_c (Figure 3):

i) a deforested and untreated soil (hereafter indicated as "D", and assumed as the condition potentially showing the highest rill erosion)

ii) a natural forest (“NF”) soil supporting one of the following species: *P. persica*, *P. taeda*, *C. betulus*, *C. ambigue*, *R. persicus*, *P. heterochroma*, *F. orientalis*, *A. subcordata*, *B. plumose*, *G. caspica*, and *S. ebulus*

iii) a forest soil planted with *Q. castaneifolia*, *A. glutinosa* or *Z. carpinifolia* (“PF”)

iv) soils deforested and then subjected to one of the treatments indicated in section 2.3 and Figure 3 (“D+T”).



Experimental soil conditions	Deforested and untreated soil (reference)	
	Soil of natural forests	*P. persica*
		P. taeda
		C. betulus
		Q. castaneifolia
		C. ambigue
		R. persicus
		P. heterochroma
		F. orientalis
		A. subcordata
		B. plumose
		G. caspica
		S. ebulus
	Soil of planted forests	*A. glutinosa*
		Z. Carpinifolia
	Deforested and treated soil	inoculation with bacillus polymyxa strain BcP26 and planting *Zoysia* grass seeds
		inoculation with the *Bacillus subtilis* OSU 142
		application of rice husk biochar
		hydromulching using *Zoysia grass* seeds and additives
		hydromulching using *Zoysia grass* seeds and addition of silica nanoparticles

Figure 3 - Scheme of the soil conditions adopted for flume experiments on soil samples collected at the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran).

2.2. Soil sampling

In a sub-area of 15 ha in the study area, soil was collected using small shovelfuls and brought to the laboratory by a van. for treatments in the deforested hillslopes at a depth between 0 and 20 cm and transported to the laboratory. For each sampling area, rocks, weeds, and litter were removed from the soil surface before soil extraction.

Concerning soil sampling in deforested and untreated areas ("D") as well as natural ("NF") and planted ("PF") forests, five pairs of samples were collected for five trees of each vegetal species (totalling 50 samples per species). In more detail, two quadrats (1 × 1 m and 2 × 2 m) were placed on soil around each tree. Two soil samples were collected in the vertices of the diagonal of the first quadrat, and two others in the opposite diagonal of the second quadrat. The fifth sample was collected very close to the trunk (0.10-0.20 m). One of each pair of samples was used for the subsequent soil and plant root analysis, and the other for the determination of rill detachment capacity by flume experiments.

In all cases, the samples were collected, using a steel ring (0.1 m in diameter and 0.05 m in height) at a depth between 0 and 20 cm.

2.3. Description of soil treatments

The following five treatments were tested:

i) Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds (hereafter indicated with "D-Thbp", where "D" stands for "deforested" and the following letters indicate the treatment type)

ii) Inoculation with *Bacillus subtilis OSU 142* ("D-TBs")

iii) Application of rice husk biochar ("D-Trhb")

iv) Hydromulching using *Zoysia* grass seed ("D-Thzg")

v) Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles ("D-Thsn").

2.3.1. Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds

The bacterial polymyxa strain BcP26, which is considered one of the plant growth-promoting strains (Egamberdiyeva, 2007), was grown in a glycerol peptone medium and agitated on a rotary shaker (120 rpm) throughout 48 hours. Seeds of *Zoysia* grass were dipped for 30 minutes in the bacterial suspension (1 × 1010 CFU/mL, Colony Forming Units) (Fonseca et al., 2022). Then, the seeds were sprayed on the plot surface.

2.3.2. Inoculation with *Bacillus subtilis OSU 142* ("D-TBs")

The *Bacillus subtilis* OSU 142 isolate was obtained using Nutrient Agar general medium (Eevers et al., 2015), according to the standard protocols reported by (Benson, 1973), and then stored at -80 °C. A pure culture of *B. subtilis* grew in a liquid nutrient broth medium at 28 °C (Garbeva et al., 2011) until a density of 108 CFU/mL after dilution. The surface of the treated soil was inoculated with 500 mL of the broth medium (Valencia et al., 2014) by spraying technique throughout an incubation period of 100 days, which is considered a suitable period to make the bacterial treatment effective (Hacimüftüoğlu and Canbolat, 2022) and kept at a water content equal to the field capacity.

2.3.3. Application of rice husk biochar ("D-Trhb")

In the case of the treatment "D-Trhb", the biochar was produced from rice husk by an electrical muffle furnace. The peak temperature was set to 500 °C and the pyrolysis process lasted from 30 to 45 min, according to the procedure by (Ghorbani et al., 2019). Immediately after production, biochar was applied to the plots at 3% (w/w).

2.3.4 Hydromulching using *Zoysia* grass seed ("D-Thzg")

Water, grass of *Zoysia* grass, organic binder, cellulose fibres, bio-humus, starter fertilizer, super absorbent, and green dye were mixed to prepare the substrate for the mulch, following the hydromulching international protocol (Parsakhoo et al., 2018; Sheldon and Bradshaw, 1977). *Zoysia* grass, growing in the warm season, was selected due to its deep root system and hard leaves, which make a dense vegetal cover on the soil surface. An organic binder was added to stabilize the soil aggregates. Cellulose fibres and bio-humus were mixed to enhance germination of the grass seeds and as absorbent mats, respectively. Starter fertilizer and super absorbent were supplied to feed seedlings and increase the water-holding capacity of soil, respectively. The hydromulch mixture was applied to plots at a dose of approx. 40 g/ha (400 kg/h) in 4 L of water, following the indications by (Holt et al., 2005; Ricks et al., 2020). Once grass grew, its leaves were removed from the soil surface using scissors.

2.3.5. Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles ("D-Thsn").

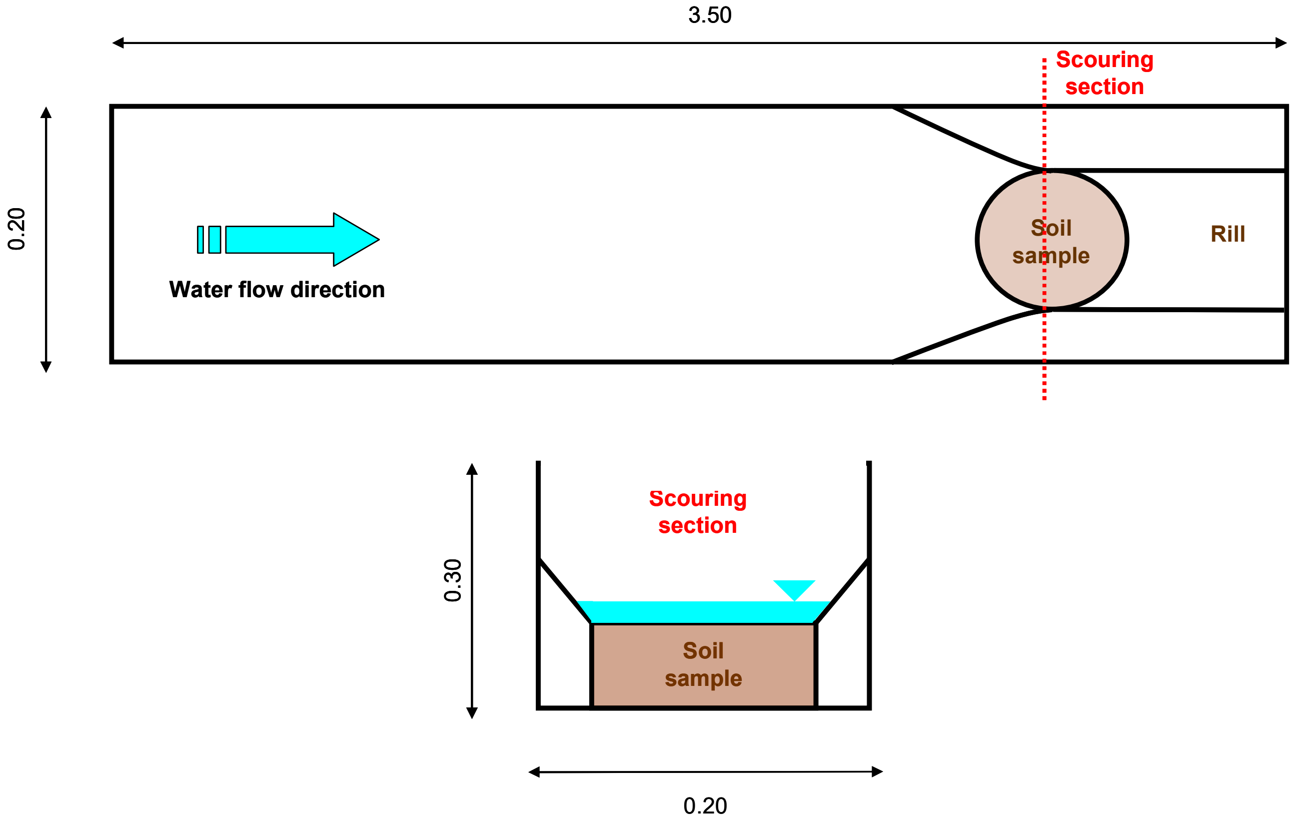
Silica nanoparticles were synthesised from rice husk (Sharma et al., 2019). The husk was boiled in a HCl solution (10% w/w) for 2 hours in open air, rinsed with deionized water, and then dried at a temperature of 100 °C for 24 hours in a conventional electric oven. The dried rice husk was pyrolyzed by an electrical muffle furnace at a peak temperature of 700 °C for two hours, according to the procedure reported by (Wang et al., 2012) until a white powder was obtained. The powder was mixed with water and sprayed on the plot at a concentration of 100 mg/L).

2.4. Plot preparation

After sampling, the soil was sterilised in an autoclave at a temperature of 121 °C for 15 minutes. Then, the soil collected in the study areas (about 240-250 kg per sampling operation and treatment) was manually mixed, placed and levelled in five small plots, each of about 1.5 m x 0.5 m with sides of 0.2 m (Figure 4a). The plots were made of timber planks and placed on concrete blocks. The soil of plots was then compacted with a concrete roller, to achieve a bulk density equal to that measured at the study area. To set the water content of soil at the field capacity, all plots were subjected to wetting and drying cycles in the open air for 24 hours, and then, placed in a room with a controlled temperature of 25 °C throughout 10 months. After this period, 50 soil samples, of the same size as for sampling in deforested and untreated areas ("D") as well as natural ("NF") and planted ("PF") forests, were extracted from each of the treated plots, using the same steel ring for the subsequent flume experiments and determination of soil properties and root system characteristics in the laboratory.

(a)

(b)



(c)

Figure 4 - Experimental plot with soil treated with hydromulching (a), flume for measuring rill detachment capacity on soil samples (picture, b, and scheme, c).

2.4. Analysis of soil and plant root properties

After collection, the soil samples collected in the plots (for treatments) or in field (in deforested and untreated areas ("D") as well as natural ("NF") and planted ("PF") forests were transported to the Soil Testing Laboratory of the College of Agriculture of the Guilan University to measure the main physical and chemical properties of the sampled soils as well as the plant root characteristics.

Concerning soil analysis, the samples were air-dried and sieved through a 2-mm mesh. Then, the content in organic carbon (OC), aggregate stability in water (WSA) and bulk density (BD) of samples were measured. These key parameters were chosen among the large number of soil parameters impacted by rill erosion and soil conservation practices, considering their large recurrence and application in relevant studies (e.g., Gyssels et al., 2005; Owoputi and Stolte, 1995).

The Walkley-Black technique, based on the potassium dichromate colorimetric method, was used to measure soil OC (Allison, 1965). The WSA (Kirkham et al. 1959) was determined using the washing method over a 1-mm sieve, while BD was estimated using the oven-drying method applied to the sieved soil at 65 °C (Kemper and Rosenau, 1986). For the characterisation of plant root system in the samples, the samples were first oven-dried at 60 °C for 48 hours, and then weighted for several times until a constant value. Root weight density (RWD) was measured by the washing method over a 1-mm sieve and subsequent oven-drying (at 65 °C for 24 hours).

2.5. Measurement of rill detachment capacity

Lab measurements allow a better control of hydraulic and morphological variables driving rill erosion compared to natural conditions (e.g., using rainfall simulators in fields), and for this reason were adopted for this investigation. In the laboratory of Guilan University, an experimental flume with a rectangular cross-section (length of 3.5 m and width of 0.2 m) was used (Figures 4b and 4c). A 5-mm soil layer was put over the flume bed, in order to reproduce the natural roughness of the soil (Zhang et al., 2002). Different water flows were generated on adjustable soil slopes (0 to 38%).

The experimental procedure was set according to Parhizkar et al. (2020a). The surface of each sample, sieved through a 2-mm mesh, was wetted by light spraying for 24 hours. The wetted sample in the steel ring was then placed in a hole (0.1 m in diameter) of the flume bed, about 0.5 m far from the bottom outlet of the flume, and then the ring was removed. The upper surface was at the same level as the flume bed surface. Then, the sample was covered by a plastic panel, to avoid scouring before the experiment during the procedure to adjust the water flow at the desired value.

Using tap water poured upstream of the flume, D_c was measured over a period between 5 s and 5 minutes. After the experiment start, a steady water flow rate was expected, by controlling the vertical fluctuations of the water depth. The values of the water volume were measured five times per experiment, collecting the water into a graduated plastic cylinder.

After removing the panel, the experiment started with soil scouring. To reduce the influence of uneven detachment within the sample, the time of the experimental test was controlled by the scouring depth for each soil sample. The experimental test ended when the eroded soil depth was 0.015 m (Nearing *et al.*, 1991; Zhang *et al.*, 2002).

After each test, the wet soil sample was extracted from the flume bed and then oven-dried at 105 °C for 24 h to measure its dry weight. D_c was calculated using equation (1):

$$D_c = \frac{\Delta M}{A \cdot \Delta t} \tag{1}$$

ΔM [kg] being the dry weight of detached soil, Δt [s] the experiment duration, and A [m^2] the area of the soil sample. Theoretically, cos θ must be added as a correction factor to Eq. (1), to consider the effect of the bed slope (tan θ) on the projection of the sample area over the horizontal plane. However, due to the very low slope angle (< 16.3°), the correction factor was very close to one.

For each soil sample subjected to flume experiments, five water flow rates per unit width of flume (WFR, 0.27 ± 0.06, 0.37 ± 0.07, 0.48 ± 0.06, 0.58 ± 0.05, and 0.69 ± 0.05 L m^{-1} s^{-1}) and five soil slope gradients (SS, 5.9 ± 2.52%, 11.1 ± 2.92%, 17.6 ± 2.11%, 24.5 ± 3.12%, and 31.7 ± 3.04%) were simulated, each WFR and SS in four replicates. Therefore, 2000 flume experiments on as many soil samples (20 soil conditions × 5 water flow rates × 5 soil slope × 4 replications) were carried out. The 20 soil conditions are hereafter indicated as “D”, “NF” (12 species), “PF” (two species), and “D-Thbp”, “D-TBs”, “D-Trhb”, “D-Thzg” and “D-Thsn” (five treatments).

2.6. Data processing

The “D” soil condition was assumed as the “reference” value for the four key soil properties and D_c. For each flume experiment, the so-called “effect size” (e.g., Vieira et al. 2015; Girona-García et al. 2021) was adopted to evaluate the change in a given soil property between the deforested site as well as the other 19 experimented soil conditions. This effect size was calculated as the decimal logarithm of the “response ratio” (LRR, Curtis and Wang 1998; Hedges et al. 1999) according to the following equation:

$$LRR = \log\frac{x_{SC}}{x_D} \tag{2}$$

“log” being the base-10 logarithm (which directly gives the order of magnitude of the change), “x_{SC}” being the mean value of the property measured in the site under a given soil condition, and “x_D” is the value of the same property measured in the “D” condition (Kalies et al. 2010). When LRR is positive, the value of the studied property in the given soil condition is higher compared to the “D” soil, otherwise, if LRR is negative, the value is lower under that condition. The five calculated LRRs for the soil properties analysed in this study are hereafter indicated as “LRR(D_c)”, “LRR(OC)”, “LRR(RWD)”, “LRR(WSA)” and “LRR(BD)”.

2.7. Statistical analysis

Previously, normality and homogeneity of variance in data were evaluated by Shapiro–Wilk's and Levene's tests, respectively. When the tests were not satisfied, the data were square root-transformed.

A one-way ANOVA was then applied to the LRRs of the analysed plant/soil properties and D_c, in order to identify any significant differences. The soil condition with three levels ("NF", "PF" and "D+T") was used as ANOVA factor. Pairwise comparisons were then carried out between two soil conditions, using Tukey's test (at $p < 0.05$).

Then, an analysis of correlation (using Pearson's coefficient "r") and a Principal Component Analysis (PCA) were applied to all LRRs to analyse the associations among plant/soil properties, and D_c. PCA selects a lower number of derivative variables (Principal Components, PCs) among the original parameters (Lee Rodgers and Nicewander, 1988). losing as little information as possible. In this study, PCA was carried out by standardising the original variables (expressed by different measuring units) and using Pearson's method to compute the correlation matrix. The first three PCs, explaining at least at least a percentage of 70% of the original variance, were retained.

Finally, the observations were grouped in clusters using Agglomerative Hierarchical Cluster Analysis (AHCA), a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. The agglomerative clustering groups objects in clusters, starting from each object that is progressively merged to another object based on a similarity-dissimilarity measure until all clusters are grouped into a cluster containing all objects. The result of AHCA is a tree-based representation of the objects in a so-called "dendrogram", which shows the progressive grouping of objects in clusters according to their level of similarity-dissimilarity. In this study, the Euclidean distance was used as similarity-dissimilarity measure (Zema et al., 2015).

The statistical analysis was carried out using the XLSTAT software (release 2019, Addinsoft, Paris, France).

3. Results

3.1. Changes in soil properties among the soil conditions

The ANOVA revealed that the soil conditions determined significant differences in LRRs of all plant and soil and plant root characteristics as well as in D_c ($F = 25.420$, $p < 0.0001$) (Table 2).

Table 1 reports the values of the analysed soil properties and D_c for all the flume experiments (the latter averaged by the four replicates of each experiment).

Table 1 – Results of one-way ANOVA applied to Log Response Ratios (LRR) of organic carbon (OC), bulk density (BD), water-stable aggregates (WSA) of soil, root weight density (RWD) of plants and rill detachment capacity (D_c) in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran).

Variables	**Degrees of freedom**	**Sum of squares**	**Mean squares**	**F**	**Pr > F**
LRR(OC)	2	7.346	3.673	447.411	< 0.0001
LRR(RWD)		2.359	1.179	60.287	
LRR(BD)		0.068	0.034	25.420	
LRR(WSA)		24.191	12.095	73.839	
LRR(D_c)		18.327	9.164	66.127	

Notes: LRR = Log Response Ratio; OC = soil organic carbon; BD = soil bulk density; WSA = soil water-stable aggregates; RWD = plant root weight density; D_c = rill detachment capacity of soil.

Table 2 – Main statistics of Log Response Ratios (LRR) of soil and plant root properties for different soil conditions and plant species/soil conservation treatments in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran).

LRR of soil properties	**Soil condition**	**Plant species/soil conservation treatment**	**Minimum**	**Maximum**	**Mean**	**Standard deviation**	**Coefficient of variation (0 - 1)**
Soil bulk density	Natural forest soil	*P. persica*	-0.12	-0.07	-0.10	0.01	-0.12
		P. taeda	-0.12	-0.08	-0.10	0.01	-0.09
		C. betulus	-0.12	-0.08	-0.10	0.01	-0.12
		C. ambigue	-0.18	-0.05	-0.12	0.04	-0.30
		R. persicus	-0.16	-0.07	-0.12	0.03	-0.26
		P. heterochroma	-0.17	-0.08	-0.12	0.03	-0.24
		F. orientalis	-0.18	-0.07	-0.13	0.03	-0.21
		A. subcordata	-0.22	-0.09	-0.16	0.03	-0.22
		B. plumose	-0.21	-0.09	-0.13	0.02	-0.19
		G. caspica	-0.20	-0.09	-0.14	0.03	-0.21
		S. ebulus	-0.19	-0.09	-0.13	0.03	-0.19
	Planted forest soil	*Q. castaneifolia*	-0.10	-0.07	-0.09	0.01	-0.08
		A. glutinosa	-0.11	-0.07	-0.09	0.01	-0.09
		Z. carpinifolia	-0.11	-0.08	-0.09	0.01	-0.09
	Deforested and treated soil	Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds	-0.08	-0.02	-0.04	0.02	-0.36

Soil organic carbon		Inoculation with *Bacillus subtilis OSU 142*	-0.10	-0.03	-0.07	0.02	-0.24
		Application of rice husk biochar	-0.23	-0.11	-0.17	0.03	-0.20
		Hydromulching using *Zoysia* grass seed	-0.21	-0.10	-0.15	0.03	-0.19
		Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles	-0.18	-0.07	-0.13	0.03	-0.24
	Natural forest soil	*P. persica*	-0.24	-0.14	-0.20	0.02	-0.12
		P. taeda	-0.25	-0.18	-0.21	0.02	-0.10
		C. betulus	-0.30	-0.21	-0.25	0.03	-0.11
		C. ambigue	-0.13	0.06	-0.02	0.05	-2.51
		R. persicus	-0.16	0.03	-0.06	0.04	-0.67
		P. heterochroma	-0.11	0.04	-0.05	0.04	-0.93
		F. orientalis	-0.10	0.08	0.00	0.04	13.83
		A. subcordata	-0.03	0.14	0.05	0.04	0.85
		B. plumose	-0.06	0.09	0.01	0.04	3.19
		G. caspica	-0.06	0.13	0.03	0.04	1.39
		S. ebulus	-0.09	0.10	0.00	0.05	13.61
	Planted forest soil	*Q. castaneifolia*	-0.45	-0.26	-0.34	0.06	-0.17
		A. glutinosa	-0.37	-0.22	-0.30	0.04	-0.13

		Z. carpinifolia	-0.46	-0.27	-0.35	0.05	-0.15
	Deforested and treated soil	Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds	-0.07	0.18	0.08	0.05	0.61
		Inoculation with *Bacillus subtilis OSU 142*	0.02	0.18	0.10	0.04	0.43
		Application of rice husk biochar	-0.03	0.17	0.09	0.04	0.52
		Hydromulching using *Zoysia* grass seed	-0.03	0.12	0.06	0.05	0.82
		Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles	-0.12	0.10	0.00	0.05	18.38
Root weight density	Natural forest soil	*P. persica*	0.11	0.31	0.23	0.06	0.24
		P. taeda	-0.04	0.29	0.16	0.08	0.51
		C. betulus	-0.02	0.21	0.09	0.06	0.68
		C. ambigue	-0.40	0.17	-0.07	0.14	-1.96
		R. persicus	-0.50	-0.04	-0.21	0.11	-0.53
		P. heterochroma	-0.46	0.01	-0.14	0.11	-0.81
		F. orientalis	-0.25	0.18	0.00	0.10	22.47
		A. subcordata	-0.03	0.31	0.11	0.09	0.81

	Planted forest soil	*B. plumose*	-0.12	0.27	0.04	0.09	2.40
		G. caspica	-0.10	0.28	0.05	0.09	1.74
		S. ebulus	-0.21	0.25	0.00	0.11	460.47
		Q. castaneifolia	-0.47	0.06	-0.12	0.11	-0.92
		A. glutinosa	-0.13	0.09	0.00	0.06	-37.67
		Z. carpinifolia	-0.27	0.06	-0.12	0.09	-0.79
	Deforested and treated soil	Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds	-0.16	0.45	0.16	0.12	0.73
		Inoculation with *Bacillus subtilis OSU 142*	0.00	0.41	0.21	0.09	0.43
		Application of rice husk biochar	-0.07	0.33	0.17	0.09	0.53
		Hydromulching using *Zoysia* grass seed	-0.04	0.31	0.14	0.10	0.70
		Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles	-0.22	0.20	0.01	0.09	15.32
Stability of soil aggregates in water	Natural forest soil	*P. persica*	0.25	0.83	0.51	0.14	0.28
		P. taeda	0.25	0.68	0.44	0.13	0.29
		C. betulus	0.13	0.63	0.34	0.13	0.39

Planted forest soil	*C. ambigue*	-0.46	0.20	-0.12	0.17	-1.36
	R. persicus	-1.61	-0.42	-0.86	0.28	-0.33
	P. heterochroma	-1.06	-0.33	-0.64	0.18	-0.29
	F. orientalis	-0.20	0.44	0.06	0.15	2.63
	A. subcordata	-0.17	0.42	0.05	0.14	3.02
	B. plumose	-0.32	0.21	-0.13	0.15	-1.15
	G. caspica	-1.37	-0.44	-0.80	0.26	-0.32
	S. ebulus	-1.19	-0.26	-0.63	0.20	-0.31
	Q. castaneifolia	-0.25	0.55	0.09	0.20	2.21
	A. glutinosa	0.09	0.55	0.26	0.13	0.49
	Z. carpinifolia	-0.25	0.55	0.11	0.19	1.67
Deforested and treated soil	Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds	0.07	0.59	0.34	0.13	0.39
	Inoculation with *Bacillus subtilis OSU 142*	-0.08	0.56	0.18	0.15	0.85
	Application of rice husk biochar	0.21	0.77	0.46	0.15	0.32
	Hydromulching using *Zoysia* grass seed	0.20	0.74	0.43	0.13	0.31
	Hydromulching using *Zoysia* grass seed and	0.09	0.63	0.35	0.13	0.38

		addition of silica nanoparticles					
Rill detachment capacity	Natural forest soil	*P. persica*	-2.18	-0.53	-1.06	0.43	-0.41
		P. taeda	-1.57	-0.35	-0.90	0.36	-0.40
		C. betulus	-1.40	-0.22	-0.78	0.36	-0.46
		C. ambigue	-0.98	0.14	-0.49	0.37	-0.75
		R. persicus	-0.93	0.24	-0.36	0.38	-1.05
		P. heterochroma	-0.97	0.23	-0.39	0.38	-0.99
		F. orientalis	-1.27	-0.29	-0.80	0.32	-0.39
		A. subcordata	-1.33	-0.29	-0.85	0.34	-0.40
		B. plumose	-1.22	0.00	-0.63	0.37	-0.58
		G. caspica	-1.02	0.20	-0.43	0.39	-0.90
		S. ebulus	-1.09	0.15	-0.52	0.39	-0.76
	Planted forest soil	*Q. castaneifolia*	-1.06	0.18	-0.46	0.40	-0.85
		A. glutinosa	-1.22	-0.02	-0.67	0.37	-0.55
		Z. carpinifolia	-1.13	0.12	-0.55	0.40	-0.73
	Deforested and treated soil	Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds	-0.29	-0.03	-0.17	0.07	-0.42
		Inoculation with *Bacillus subtilis OSU 142*	-0.35	-0.05	-0.18	0.08	-0.44

		Application of rice husk biochar	-0.57	-0.16	-0.32	0.10	-0.31
		Hydromulching using *Zoysia* grass seed	-0.68	-0.20	-0.36	0.10	-0.28
		Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles	-0.10	0.21	0.05	0.08	1.40

In more detail, with a specific regard to the soil properties, the LRR(BD) was always negative, showing a decrease in soil compaction in natural and planted forests and the treated sites compared to the deforested areas. The minimum LRR(BD) was found on average in NF soils (-0.123 ± 0.031) and the maximum in D+T plots (-0.112 ± 0.054), PF sites showing intermediate values (-0.089 ± 0.008) and the lowest variability among the three soil conditions. Among the treatments applied to deforested sites, the "Trhb" and "Thbp" showed the maximum and minimum LRR(BD) (-0.043 and -0.167, respectively) (Table 2 and Figure 5).

The mean value of LRR(OC) followed a gradient PF (-0.329 ± 0.055) < NF (-0.063 ± 0.109) < D+T (0.066 ± 0.058) soils. Only the deforested and treated soils showed positive LRRs for this property. It is worth highlighting that the soil conservation treatments led to a general increase in OC - shown by positive LRR(OC) - compared to the deforested areas, while in planted forests the OC content underwent a general reduction. In the treated sites, the LRR(OC) was the highest (0.102) in the "Tbs" plot, and the lowest in the "Thzg" soil (Table 2 and Figure 5).

On average, LRR(WSA) was lower in NF soils (-0.163 ± 0.509), and higher and positive in PF (0.156 ± 0.191) and D+T sites (0.350 ± 0.169). Also for this soil property, LRR(WSA) was positive in the treated areas as well as in planted forests. This shows that soil conservation and reforestation generally increase the stability of soil aggregates, while, in natural forests, some cases of WSA reductions were detected. The treatments that led to the extreme values of LRR(WSA) were "Tbs" and "Thbp" (from 0.179 to 0.457, respectively) (Table 2 and Figure 5).

Concerning the plant root characteristics, the LRR(RWD) was the highest in PF soils (-0.080 ± 0.105) and the lowest in D+T plots (-0.138 ± 0.120). The NF sites showed close and intermediate values (-0.024 ± 0.155). After the treatments, LRR(RWD) was the highest in the "Tbs" soil (0.214) and the lowest in the "Thzg" plot (0.006). In general, reforestation resulted in a decrease in RWD, while the application of soil conservation techniques increases the mean RWD, as shown by the negative and positive values of LRR(RWD) measured under those two soil conditions (Table 2 and Figure 5).

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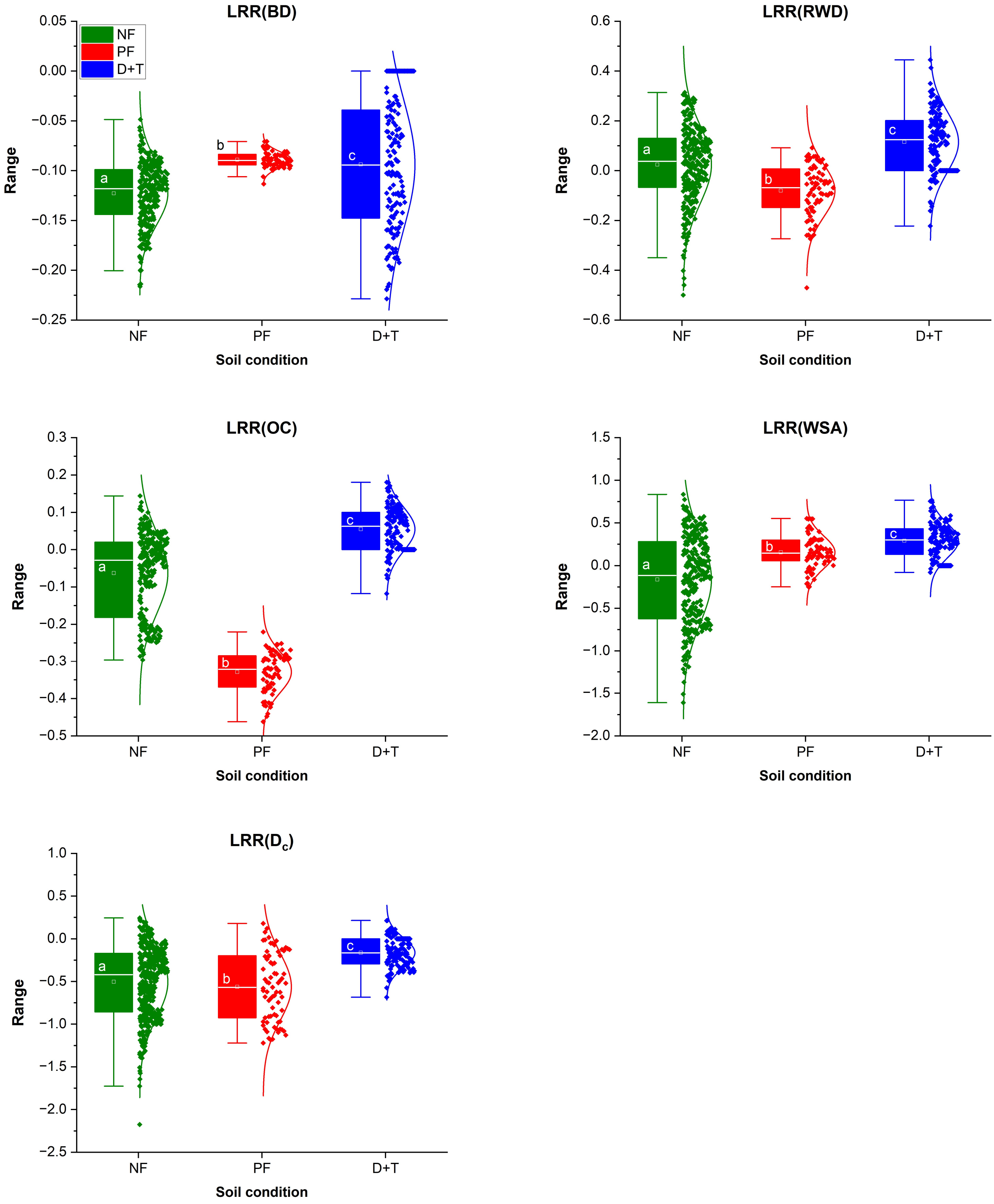
LRR(BD)
🟩 NF
🟥 PF
🟦 D+T
Range
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
a
b
c
NF
PF
D+T
Soil condition
LRR(RWD)
Range
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0.4
0.2
0.0
−0.2
−0.4
−0.6
a
b
c
NF
PF
D+T
Soil condition
LRR(OC)
Range
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0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
a
b
c
NF
PF
D+T
Soil condition
LRR(WSA)
Range
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
a
b
c
NF
PF
D+T
Soil condition
LRR(D$_c$)
Range
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0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
a
b
c
NF
PF
D+T
Soil condition

Figure 5 – Box plots of Log Response Ratios (LRR) of soil and plant root characteristics and rill detachment capacity in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran). *Different letters indicate significant differences after Tukey's tests ($p < 0.05$). The white cross indicates the mean value of data. OC = soil organic carbon; BD = soil bulk density; WSA = soil water-stable aggregates; RWD = plant root weight density;* D_c *= rill detachment capacity of soil; NF = natural forest soils; PF = planted forest soils; D+T = deforested and treated soils.*

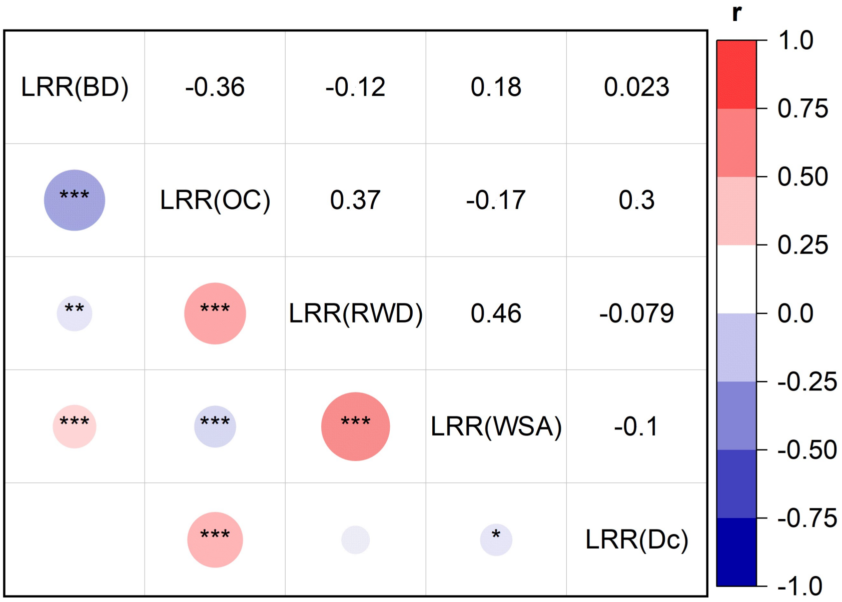
3.2. Changes in rill detachment capacity among the soil conditions

In comparison to the deforested sites, D_c underwent a noticeable reduction under all soil conditions, as shown by the negative values of LRR(D_c). This parameter was, on average, significantly lower in NF (-0.655 ± 0.429) and PF (-0.563 ± 0.393) compared to D+T sites (-0.195 ± 0.169), while no significant differences were found between PF and NF soils. This means that the presence of both natural and planted vegetation reduces by the same extent rill detachment capacity compared to the deforested areas. A lower reduction in soil erodibility is achieved by the application of soil conservation treatments. Finally, the lowest LRR(D_c) was measured under "Thsn" (-0.360) and “Thpb” (-0.320) treatments, while the minimum (0.054) under "Thzg", the “Thrb” and “Tbs” plots showing intermediate values, -0.166 and -0.183, respectively (Table 2 and Figure 5).

3.3. Correlations among the changes in soil properties and D_c

The analysis of the correlation matrix among the analysed LRRs shows significant but limited values of the ”r”" coefficient. The highest and most significant values of “r” were found for the pairs LRR(RWD) vs. LRR(WSA) (0.46, $p < 0.001$) as well as LRR(OC) on one side and LRR(BD) (-0.36, $p < 0.001$), LRR(RWD) (0.37, $p < 0.001$) and LRR(D_c) (0.3, $p < 0.001$) on the other side. All the remaining pairs were characterised by values of r lower than 0.2 (Table 3). This means that: (i) soil aggregates are more stable in soils with well-developed plant root systems; (ii) soil compaction decreases and root weight density increases in soil with higher OC; (iii) rill detachment capacity may increase in soils characterised by higher OC.

Table 3 - Pearson's correlation matrix among pairs of Log Response Ratios of soil and plant root characteristics, rill detachment capacity inthe two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran).



* p<=0.05 ** p<=0.01 *** p<=0.001

Notes: LRR = Log Response Ratio; OC = soil organic carbon; BD = soil bulk density; WSA = soil water-stable aggregates; RWD = plant root weight density; D_c = rill detachment capacity of soil.

3.4. Discrimination in soil properties and rill detachment capacity among the soil conditions

The PCA provided three Principal Components (PCs), which explain about 83% of the total variance of the original plant/soil properties and D_c; PC1 and PC2 explain 32.4% and 29.8% of this variance, and together a value of 62.2%.

LRR(BD) and LRR(OC) have high loadings on the PC1 (-0.634 and 0.887, respectively), while LRR(RWD) and LRR (WSA) noticeably influence the PC2 with positive weights (> 0.744). PC3 is significantly associated only with LRR(D_c) with a loading of 0.806 (Table 4 and Figure 6a). These loadings are in line with the correlation analysis, showing close and positive associations between WSA and RWD on one side as well as inverse relationships between OC and RWD.

Table 4 - Factor loadings of Log Response Ratios of soil and plant root characteristics and rill detachment capacity on the first three Principal Components (PC1 to PC3) provided by PCA in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran).

Original variables	Principal Components (PC)		
	PC1	PC2	PC3
LRR(BD)	**-0.634**	0.197	0.571
LRR(OC)	**0.887**	-0.100	0.106
LRR(RWD)	0.549	**0.744**	0.004
LRR(WSA)	-0.081	**0.873**	0.205
LRR(D_c)	0.350	-0.353	**0.806**

Notes: LRR = Log Response Ratio; OC = soil organic carbon; BD = soil bulk density; WSA = soil water-stable aggregates; RWD = plant root weight density; D_c = rill detachment capacity of soil. Values in bold correspond to the factor for which the factor loading is the largest for each variable.

According to the score plot of PCA, the soil samples are arranged according to the gradient PF < NF < D+T. This gradient is more evident along the first PC than PC2, according to the percent variance explained by each PC (Figure 6b). Moreover, the gradient along the PC1 shows how, in comparison to NF and PF plots, D+T soils are associated with higher values of LRR(OC) and lower LRR(BD), while the minor gradient along PC2 links the D+T samples to higher LRR(WSA) and LRR(RWD). Finally, according to the aforementioned influence of LRR(D_c) on the third PC (Table 4), the D+T soils are on average characterized by higher values of PC3 (0.886 ± 0.080, mean ± std. error) compared to NF (-0.450 ± 0.051) and PF (0.174 ± 0.086) samples. This means that the natural forests support the lowest soil erodibility, while the soil conservation treatments, which significantly reduce rill erosion compared to the deforested but untreated sites, are not able to restore the erosion rates that are typical of the natural and undisturbed areas.

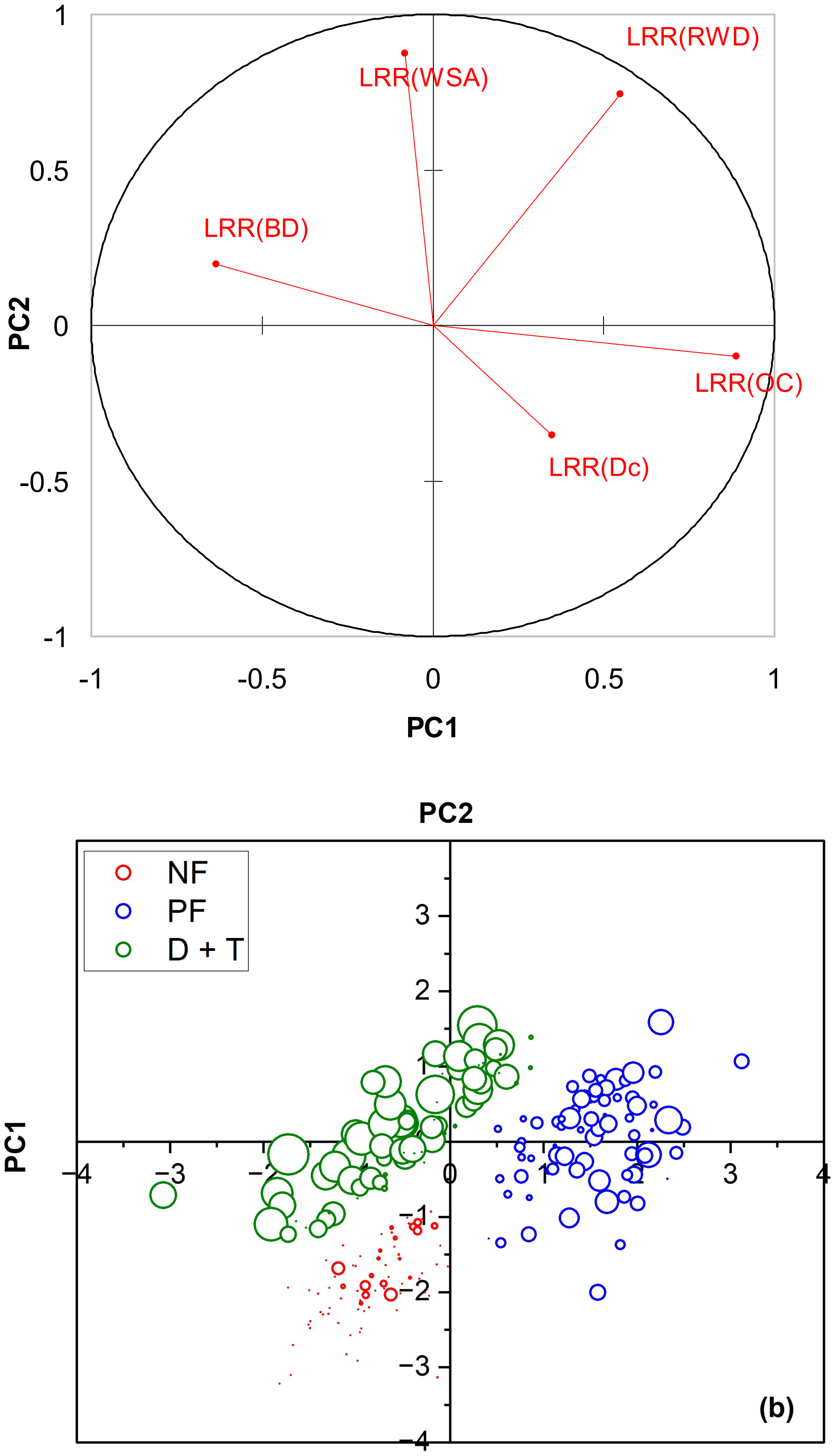
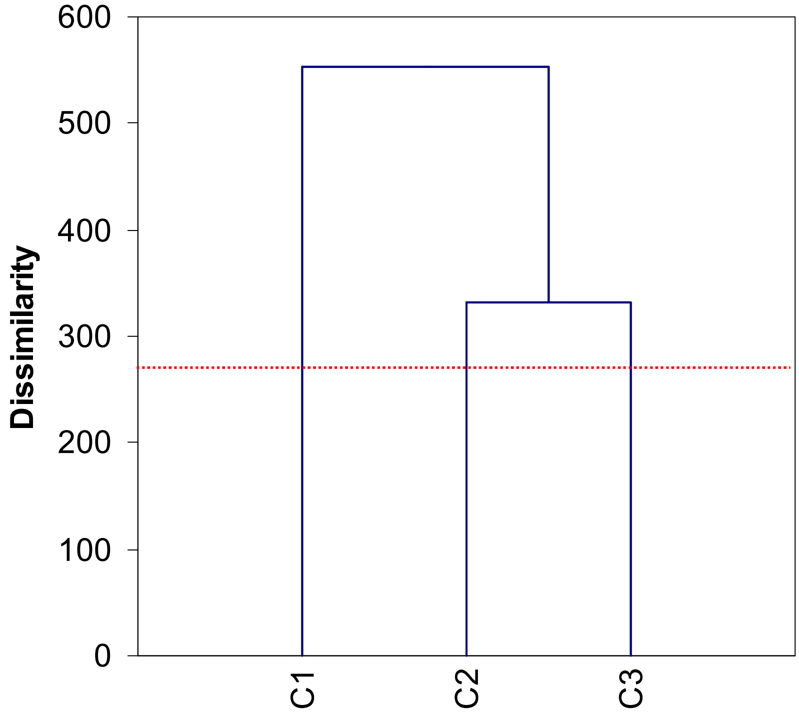


Figure 6 - Loadings of the Log Response Ratios (LRR) of soil and plant root characteristics and rill detachment capacity on the first three Principal Components (PC1 to PC3) ("a"), and score plot of

soil samples ("b") on PC1 and PC2 provided by Principal Component Analysis in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran). *Legend: OC = soil organic carbon; BD = soil bulk density; WSA = soil water-stable aggregates; RWD = plant root weight density;* D_c *= rill detachment capacity of soil; NF = natural forest soils; PF = planted forest soils; D+T = deforested and treated soils; the diameter of bubbles in the lower chart is proportional to the value of PC3.*

AHC discriminates the collected samples in three separate clusters, of which the first two clusters (C1 and C2) solely group soils sampled in natural and planted forests (> 90% of the total number of samples), while the third cluster (C3) mainly consists of D+T samples (57%). The level of dissimilarity between the first two cluster (C1 and C2) is higher compared to the third group (C3, Figure 7).



Clusters		
C1	C2	C3
NF-Pp (25)	NF-Ca (15)	NF-Ca (8)
NF-Pt (25)	NF-Rp (25)	NF-Ph (1)
NF-Cb (25)	NF-Ph (24)	NF-Fo (19)
PF-Qc (25)	NF-Fo (5)	NF-As (23)
PF-Ag (25)	NF-As (2)	NF-Bp (19)
PF-Zc (25)	NF-Bp (6)	NF-Gc (8)
NF-Ca (2)	NF-Gc (17)	NF-Se (7)
NF-Fo (1)	NF-Se (18)	D-Trhb (25)
D-Thzg (1)	D-Thbp (2)	D-TBs (25)
	D-Thsn (3)	D-Thbp (23)
	D-Thzg (8)	D-Thsn (22)
		D-Thzg (16)

Figure 7 - Dendrogram of Log Response Ratios of soil and plant root characteristics and rill detachment capacity (upper) and cluster composition provided by the Agglomerative Hierarchical Cluster Analysis (lower) in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran). *Legend: the y-axis of the dendrogram reports the similarity level, while the red dotted line the clustering level; NF = natural forest soils; PF = planted forest soils; D+T = deforested soils subjected to treatment (see section 2.2 for treatment acronyms); the number in round brackets in the cluster composition indicates the samples in each soil conditions.*

4. Discussions

4.1. Variability of soil properties, root characteristics and rill detachment capacity among the soil conditions

The deforested soils showed the highest soil erodibility and were therefore assumed as the worst condition reference. Comparing these deforested sites to the natural forests, in this investigation soil bulk density, organic carbon content and stability of soil aggregates significantly decreased on average by about 14% to 31% in natural forests, while root weight density increased on average by 6%. This lower content in OC may be explained by the higher uptake of organic matter due to the presence of vegetal species (Jarideh et al., 2021; Razzaghi et al., 2022). Since the organic matter acts as a binding agent for particles (An et al., 2010), a decrease in OC may lead to a lower stability of soil aggregates, as found in this study. The lower bulk density of natural forests may be due to the more developed root system of plants (Baets et al., 2007; De Baets et al., 2006; Wang et al., 2018; Zhang et al., 2016), shown by the increase in RWD. The higher presence of plant roots creates a system of continuous pores (Dunkerley, 2000; Gyssels et al., 2005; Shinohara et al., 2016), making forest soil looser and more porous (Hillel, 1998).

In planted forests, all key soil properties decreased (by 17%, root weight density, to 53%, soil organic carbon), except the stability of soil aggregates (which increased by 43%) in comparison to the deforested areas. In this regard, Gillespie et al. (2020), Miralles et al. (2009) and Zhang et al. (2008) stated that, although tree and herbaceous species support soil quality, their effects are different between planted and natural species. Significantly lower soil organic carbon and root weight density, but higher soil bulk density and stability of soil aggregates were found by Parhizkar et al. (2021c, 2021a) in reforested sites compared to natural forests.

Assuming again the deforested soil as a reference, the beneficial effects of treatments on the studied soil properties and plant root characteristics are clear from this study. The treated soils showed increases in soil organic carbon (+16%), root weight density (+38%) and stability of soil aggregates (+124%) as well as a decrease in soil bulk density (-23%). These effects are specifically due to the supply of additives and inoculation with bacteria, but also the effects of grass roots in the hydromulched sites may have supported the positive changes in the studied soil and plant characteristics. The specific analysis of the most influential mechanisms on each parameter shows how each treatment has improved the overall soil quality. In more detail, biochar, thanks to its stable structure, has directly supplied organic matter to soil (Zeraatpisheh et al., 2021), and reduced the soil bulk density by increasing the volume of the soil-biochar mixture (Ghorbani et al., 2019), thus improving the agronomic conditions of the soil (Nguyen et al., 2009). Silicon supply with silica nanoparticles to soil has presumably increased the availability of nutrient elements and root uptake in the rhizosphere, as also demonstrated by Pavlovic et al. (2021). Soil inoculation with rhizobacteria could have significantly increased the growth rate of several root characteristics of plants (Chowdhury et al., 2015; Kesaulya et al., 2018; Márquez et al., 2020), and caused significant increases in root weight density. *Bacillus subtilis* has promoted the growth of roots by the production of different metabolites (Liu et al., 2020), and increased the diameter of aggregates compared to untreated soils (Hacimüftüoğlu and Canbolat, 2022), due to the production of polysaccharides or glycoprotein substances that coat the surface of soil particles and develop soil structure by binding soil particles together (Cania et al., 2019; Erktan et al., 2020). According to (Artyszak and Gozdowski, 2020) and (Canbolat et al., 2006), bacterial activity significantly decreases soil bulk density and increases porosity of soil. The beneficial effects of hydromulching (with or without inoculation) on soil compaction and stability of aggregates may be due to the higher content in organic carbon and density of grass roots, which is in line with the findings of other authors (Baets et al., 2007; De Baets et al., 2006; Wang et al., 2018; Zhang et al., 2016).

Under all soil conditions, rill detachment capacity was noticeably lower compared to the deforested and untreated sites. Natural and planted forests showed a similar decrease in rill erodibility (-70 to 80%) and a much lower reduction in D_c (-36%) was measured in the treated areas. The literature has clearly shown that forest soils with different species show noticeable changes in D_c (e.g., Gyssels et al., 2005; Gyssels and Poesen, 2003; Shabanpour et al., 2020), and these changes are associated with the actions of plant roots having different characteristics among species (Li et al., 2015; Wang et al., 2018; Zhang et al., 2013). This is confirmed by this study, where D_c in natural forests was lower compared to reforested sites, while the root weight density was in soils supporting natural species. Conversely, the lower stability of soil aggregates measured in soils with planted species generally limited the root growth, and plant cover and biomass in reforested soils. According to Jackson et al. (2005) and van Dijk and Keenan (2007), the differences in aggregate stability of soils between planted and natural forests may be due to the differences in water cycles.

The effects of treatments on soil erodibility are generally beneficial and effective at contrasting soil degradation in forestlands, as shown by the significant decrease in D_c compared to the untreated soils. Also for this soil condition, the reduction in soil erodibility should be associated with the lower bulk density, higher stability of aggregates and more developed plant root system. More specifically, in the case of the application of biochar, Jien and Wang (2013) found that the significant improvement in the physical and chemical properties of treated soils compared to degraded sites led to reductions in erosion rates, thanks to the increase in macro-aggregates after substrate application. When soil was supplied with silica nanoparticles, Mathur and Roy (2020) and Mustafa et al. (2021) detected a stronger root system with more developed characteristics of roots in the soil. Also under soil inoculation with *Bacillus subtilis* the root system is more developed and thus more effective at supporting plant growth and health (e.g., Leung et al., 2015; Sun et al., 2022; Vannoppen et al., 2017). In the case of soil treatment with *Bacillus subtilis*, the decrease in soil erodibility is likely due to significant changes in the physical properties of soils (Hashem et al., 2019; Liu et al., 2022; Mahapatra et al., 2022), such as the aggregate stability and bulk density.

4.2. Associations among the analysed soil properties, root characteristics and rill detachment capacity and discrimination of the tested soil conditions

The associations between the pairs of the soil properties and root characteristics, shown by the correlation matrix, were lower than expected, considering that the literature has evidenced the reciprocal effects among soil properties and root characteristics and soil erodibility. The relatively low values of the coefficients of correlations may be explained by the large variability in the soil properties and root characteristics among the large number of different soil conditions explored in this study. Sampling was carried out in soil supporting 14 different vegetal species and subjected to five different treatments, and this variability may reflect the complex physico-chemical and biological processes underlying soil erosion. In accordance with our study, other authors showed that the variability in D_c among deforested soils, and sites with natural or planted species or plots treated with soil conservation practices is influenced by the associated changes in several properties of soil. For instance, in line with this study, several authors reported significant inverse correlations between the stability of aggregates and D_c (e.g., Guo et al., 2021; Torri et al., 1995; Zhang et al., 2008), and also Li et al. (1992) demonstrated that the soil resistance to rill erosion increases with the aggregate stability. Many studies have also reported that the characteristics of plant roots that are variable among different soil conditions can influence soil detachment capacity. For example, Burak et al. (2021) and Shinohara et al. (2016) found that the soil detachment rates significantly decrease as plant root length increases, although this association was not significantly evident in this study.

The results of PCA are in line with those of correlation analysis of this study, since the two first Principal Components (which are by definition derivative uncorrelated variables) are individually associated with different pairs of soil properties (soil bulk density and organic carbon on one side, as well as root weight density and stability of soil aggregates on the other side), while the PC3 is influenced only by D_c (showing a weaker correlation to the remaining soil properties).

The application of soil conservation treatments to the deforested soils played a significant role in discriminating treated sites on one side, and untreated (with natural or planted species) soils on the other side. However, this distinction is sharp only for the soil properties and root characteristics, but less when all the studied variables are included. This is clearly shown by the low overlap among the three soil conditions in the PC1-PC2 charts (considering that only soil properties and root characteristics are significantly associated with the main PCs), while the three groups are not fully discriminated by the AHCA that clustered the observations in non-homogenous groups in terms of soil conditions). This means that the presence of vegetation (natural or deforested) and the application of soil conservation treatments lead to different effects on soil properties and plant root characteristics, while rill detachment capacity is not sharply variable among the three soil conditions.

4.3. Limitations and practical implications of the study

To the authors' best knowledge, this is the first comprehensive analysis of a large dataset of different conditions (two thousand samples of soil and as many flume experiments from 20 conditions, consisting of soils supporting 14 vegetal species and 5 soil treatments plus deforested areas) in deforested lands that have explored the changes in key soil and root properties, and rill detachment capacity due to soil conservation treatments and different vegetation characteristics. This is important from a scientific point of view, because this gives land managers comparable (thanks to the standardised experimental conditions) and quantitative (that is, based on measurable variables) information about the changes in soil properties and erodibility expected in a natural or reforested area or in a site subjected to a soil treatment after deforestation.

However, the main limitations of the study should be also acknowledged. First, the samples were collected only in one study area, and a better generalisation and transferability of the study findings would require similar investigations in other environmental contexts with different soil types, weather conditions, and plant species. Second, the rill detachment capacity was measured using flume experiments on very small soil samples. This can lead to measurement errors due to the small scale and working conditions of the experimental device, which means that the collected data and results, although being indicative and quantitative, can not fully reproduce the environmental conditions and large spatial scales, where the rill detachment process acts.

Despite these limitations, the study has indicated that the presence of both natural and planted vegetation can reduce the rill detachment capacity after deforestation, while the soil conservation techniques show a lower reduction in soil erodibility. Among these treatments, hydromulching with addition of silica nanoparticles and inoculation with *bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds are the most effective techniques, while hydromulching with *Zoysia* grass may instead result in an increase in D_c.

5. Conclusion

In relation to the three specific objectives inspiring this study, the flume experiments carried out on soil sampled in Northern Iran have shown that:

(i) the rill detachment capacity significantly decreases in natural and planted forests compared to the deforested soils, while, under soil conservation practices, the decrease is much lower and rill detachment can never be the same as in undisurbed forest sites; this decrease in D_c results from significant changes in some key soil properties and plant root characteristics, especially the root weight density and soil bulk density

(ii) in spite of noticeable variations in all soil and root properties among the analysed conditions, the correlations among the variables were lower than expected, presumably due to the large variability in the soil conditions explored as well as the high number of tested samples

(iii) reforestation and soil treatments applied to the deforested sites, altough improving soil erodibilty, do not create a significant discrimination compared to both deforested areas and soils supporting with natural species, as demonstrated by a quantitative approach using multivariate statistics; therefore, we can conclude that the changes in soil properties due to plant species and soil management as well as the associated variability in rill detachment are not of the same magnitude, and show a great dependence on the specific soil condition and treatment.

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Author contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Misagh Parhizkar and Demetrio Antonio Zema. The first draft of the manuscript was written by Misagh Parhizkar, and all authors commented on previous versions of the manuscript. The final revision was made by Manuel Esteban Lucas Borja and Demetrio Antonio Zema. All authors read and approved the final manuscript.

Statement of conflict of interest

The authors declare no conflict of interest.

Data availability

Data will be made available upon request to the authors.

List of abbreviations

D = Deforested soil
D+T = Soil deforested and treated
NF = Natural forest soil
PF = Planted forest soil
Pp = *P. persica*
Pt = *P. taeda*
Cb = *C. betulus*
Ca = *C. ambigue*
Rp = *R. persicus*
Ph = *P. heterochroma*
Fo = *F. orientalis*
As = *A. subcordata*
Bp = *B. plumose*
Gc = *G. caspica*
Se = *S. ebulus*
Qc = *Q. castaneifolia*
Ag = *A. glutinosa*
Zc = *Z. carpinifolia*

D-Thbp = Inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds

D-TBs = Inoculation with *Bacillus subtilis OSU 142*

D-Trhb = Application of rice husk biochar

D-Thzg = Hydromulching using *Zoysia* grass seed

D-Thsn = Hydromulching using *Zoysia* grass seed and addition of silica nanoparticles

LRR = Log Response Ratio

OC = Soil organic carbon

BD = Soil bulk density

WSA = Stability of soil aggregates in water

RWD = Root weight density of plants

D_c = Rill detachment capacity

SUPPLEMENTARY INFORMATION

Table 1.SI – Mean value of soil properties, plant root characteristics and rill detachment capacity for different soil conditions in the two study areas (Saravan and Saqalaksar Forest Parks, Guilan Province, Northern Iran).

Plot	Soil condition	Water flow rate ($L\ s^{-1}\ m^{-1}$)	Soil slope (%)	Soil bulk density ($kg\ m^{-3}$)	Soil organic carbon (%)	Root weight density ($kg\ m^{-3}$)	Stability of soil aggregates in water (0 to 1)	Rill detachment capacity ($kg\ s^{-1}\ m^{-2}$)
1	Natural forest soil	<0.3	<10	1215	1.08	0.86	0.85	0.000
2	(*P. persica*)	<0.3	10-15	1221	1.16	0.87	0.92	0.000
3		<0.3	15-20	1225	1.14	0.89	0.88	0.001
4		<0.3	20-30	1216	0.97	0.82	0.75	0.001
5		<0.3	>30	1218	1.20	0.71	0.89	0.001
6		0.3-0.4	<10	1214	1.14	0.88	0.81	0.002
7		0.3-0.4	10-15	1221	1.14	0.95	0.92	0.002
8		0.3-0.4	15-20	1211	1.23	0.88	0.82	0.002
9		0.3-0.4	20-30	1210	1.14	0.89	0.92	0.003
10		0.3-0.4	>30	1210	1.14	0.91	0.80	0.003
11		0.4-0.5	<10	1211	1.10	0.82	0.81	0.004
12		0.4-0.5	10-15	1217	1.05	0.85	0.75	0.004
13		0.4-0.5	15-20	1221	1.12	0.89	0.87	0.005
14		0.4-0.5	20-30	1229	1.03	0.79	0.85	0.005
15		0.4-0.5	>30	1224	1.12	0.83	0.78	0.006
16		0.5-0.6	<10	1254	1.13	0.89	0.93	0.006
17		0.5-0.6	10-15	1274	1.04	0.87	0.84	0.007
18		0.5-0.6	15-20	1263	1.13	0.95	0.83	0.007
19		0.5-0.6	20-30	1214	1.04	0.86	0.87	0.008
20		0.5-0.6	>30	1215	1.22	0.87	0.70	0.008
21		>0.6	<10	1298	1.13	0.91	0.71	0.010
22		>0.6	10-15	1297	1.06	0.96	0.92	0.015
23		>0.6	15-20	1296	0.95	0.87	0.72	0.018

24		>0.6	20-30	1214	1.14	0.92	0.92	0.022
25		>0.6	>30	1215	1.22	0.96	0.74	0.025
1	Natural forest soil (*P. taeda*)	<0.3	<10	1255	1.09	0.82	0.81	0.000
2		<0.3	10-15	1241	1.02	0.69	0.61	0.001
3		<0.3	15-20	1255	1.07	0.54	0.82	0.001
4		<0.3	20-30	1251	1.08	0.56	0.61	0.001
5		<0.3	>30	1256	1.04	0.72	0.86	0.002
6		0.3-0.4	<10	1241	1.06	0.53	0.63	0.002
7		0.3-0.4	10-15	1221	1.08	0.75	0.77	0.003
8		0.3-0.4	15-20	1245	1.12	0.85	0.75	0.003
9		0.3-0.4	20-30	1248	1.07	0.85	0.63	0.004
10		0.3-0.4	>30	1246	1.06	0.86	0.75	0.004
11		0.4-0.5	<10	1247	1.07	0.85	0.74	0.005
12		0.4-0.5	10-15	1254	1.06	0.78	0.71	0.005
13		0.4-0.5	15-20	1253	1.08	0.81	0.72	0.006
14		0.4-0.5	20-30	1241	1.03	0.81	0.69	0.006
15		0.4-0.5	>30	1252	1.01	0.75	0.69	0.007
16		0.5-0.6	<10	1246	1.10	0.71	0.85	0.008
17		0.5-0.6	10-15	1241	1.08	0.70	0.88	0.008
18		0.5-0.6	15-20	1241	1.14	0.72	0.61	0.009
19		0.5-0.6	20-30	1255	1.07	0.75	0.62	0.009
20		0.5-0.6	>30	1262	1.08	0.88	0.89	0.010
21		>0.6	<10	1211	1.07	0.82	0.74	0.016
22		>0.6	10-15	1222	1.12	0.73	0.75	0.023
23		>0.6	15-20	1251	1.07	0.76	0.74	0.026
24		>0.6	20-30	1238	1.06	0.71	0.57	0.029
25		>0.6	>30	1215	1.11	0.86	0.54	0.034
1	Natural forest soil (*C. betulus*)	<0.3	<10	1221	0.99	0.63	0.63	0.001
2		<0.3	10-15	1262	1.00	0.60	0.58	0.001
3		<0.3	15-20	1268	1.09	0.62	0.62	0.001
4		<0.3	20-30	1222	1.01	0.63	0.72	0.002
5		<0.3	>30	1211	0.94	0.71	0.55	0.002
6		0.3-0.4	<10	1245	0.99	0.71	0.48	0.003
7		0.3-0.4	10-15	1265	1.01	0.62	0.41	0.004

8		0.3-0.4	15-20	1265	0.95	0.74	0.42	0.004
9		0.3-0.4	20-30	1265	0.99	0.64	0.54	0.005
10		0.3-0.4	>30	1251	1.01	0.61	0.53	0.005
11		0.4-0.5	<10	1268	1.00	0.63	0.59	0.006
12		0.4-0.5	10-15	1267	1.03	0.65	0.57	0.007
13		0.4-0.5	15-20	1265	1.02	0.68	0.57	0.007
14		0.4-0.5	20-30	1271	0.96	0.64	0.58	0.007
15		0.4-0.5	>30	1270	0.98	0.61	0.52	0.008
16		0.5-0.6	<10	1263	1.06	0.59	0.56	0.009
17		0.5-0.6	10-15	1243	1.01	0.63	0.54	0.009
18		0.5-0.6	15-20	1255	1.00	0.62	0.53	0.010
19		0.5-0.6	20-30	1269	1.01	0.63	0.53	0.012
20		0.5-0.6	>30	1275	1.01	0.60	0.55	0.015
21		>0.6	<10	1285	0.94	0.61	0.75	0.022
22		>0.6	10-15	1212	1.01	0.64	0.47	0.031
23		>0.6	15-20	1255	1.00	0.61	0.62	0.037
24		>0.6	20-30	1251	0.96	0.62	0.63	0.043
25		>0.6	>30	1212	1.00	0.63	0.63	0.048
1	Natural forest soil (*C. ambigue*)	<0.3	<10	1194	1.37	0.32	0.29	0.002
2		<0.3	10-15	1340	1.56	0.26	0.20	0.003
3		<0.3	15-20	1168	1.72	0.56	0.19	0.003
4		<0.3	20-30	1048	1.62	0.52	0.23	0.004
5		<0.3	>30	1247	1.90	0.52	0.20	0.004
6		0.3-0.4	<10	1332	1.63	0.32	0.20	0.005
7		0.3-0.4	10-15	1193	1.44	0.26	0.18	0.006
8		0.3-0.4	15-20	1174	1.85	0.56	0.22	0.007
9		0.3-0.4	20-30	1214	1.65	0.42	0.22	0.008
10		0.3-0.4	>30	1090	1.81	0.46	0.22	0.008
11		0.4-0.5	<10	1090	1.68	0.41	0.10	0.008
12		0.4-0.5	10-15	1162	1.62	0.45	0.19	0.009
13		0.4-0.5	15-20	1354	1.50	0.32	0.24	0.009
14		0.4-0.5	20-30	1335	1.67	0.33	0.14	0.010
15		0.4-0.5	>30	1351	1.32	0.22	0.11	0.010
16		0.5-0.6	<10	1166	1.79	0.66	0.17	0.019

17		0.5-0.6	10-15	1053	1.95	0.75	0.23	0.032
18		0.5-0.6	15-20	1282	1.78	0.47	0.22	0.039
19		0.5-0.6	20-30	1196	1.70	0.44	0.23	0.042
20		0.5-0.6	>30	1237	1.89	0.51	0.20	0.048
21		>0.6	<10	1206	1.77	0.52	0.19	0.051
22		>0.6	10-15	1121	1.81	0.56	0.17	0.056
23		>0.6	15-20	1163	1.64	0.45	0.15	0.063
24		>0.6	20-30	1068	1.97	0.56	0.25	0.069
25		>0.6	>30	1159	1.74	0.46	0.25	0.073
1	Natural forest soil (*R. persicus*)	<0.3	<10	1275	1.49	0.38	0.05	0.003
2		<0.3	10-15	1311	1.59	0.31	0.04	0.003
3		<0.3	15-20	1137	1.68	0.37	0.04	0.004
4		<0.3	20-30	1112	1.65	0.39	0.04	0.004
5		<0.3	>30	1114	1.53	0.39	0.01	0.005
6		0.3-0.4	<10	1144	1.58	0.39	0.01	0.005
7		0.3-0.4	10-15	1167	1.50	0.31	0.05	0.006
8		0.3-0.4	15-20	1307	1.43	0.21	0.06	0.007
9		0.3-0.4	20-30	1324	1.28	0.19	0.04	0.009
10		0.3-0.4	>30	1178	2.00	0.59	0.04	0.009
11		0.4-0.5	<10	1332	1.57	0.35	0.02	0.010
12		0.4-0.5	10-15	1146	1.64	0.36	0.06	0.013
13		0.4-0.5	15-20	1145	1.40	0.24	0.04	0.018
14		0.4-0.5	20-30	1229	1.49	0.22	0.04	0.024
15		0.4-0.5	>30	1093	1.51	0.39	0.02	0.029
16		0.5-0.6	<10	1109	1.65	0.35	0.05	0.038
17		0.5-0.6	10-15	1274	1.72	0.45	0.04	0.048
18		0.5-0.6	15-20	1284	1.34	0.21	0.05	0.055
19		0.5-0.6	20-30	1158	1.40	0.19	0.06	0.059
20		0.5-0.6	>30	1158	1.42	0.31	0.06	0.063
21		>0.6	<10	1249	1.54	0.31	0.04	0.065
22		>0.6	10-15	1145	1.42	0.33	0.04	0.068
23		>0.6	15-20	1142	1.39	0.31	0.04	0.071
24		>0.6	20-30	1248	1.44	0.32	0.04	0.077
25		>0.6	>30	1133	1.61	0.35	0.02	0.087

1	Natural forest soil (*P. heterochroma*)	<0.3	<10	1188	1.69	0.39	0.10	0.003
2		<0.3	10-15	1233	1.54	0.39	0.06	0.003
3		<0.3	15-20	1092	1.58	0.45	0.06	0.003
4		<0.3	20-30	1311	1.38	0.21	0.06	0.004
5		<0.3	>30	1283	1.41	0.19	0.06	0.004
6		0.3-0.4	<10	1083	1.71	0.59	0.09	0.005
7		0.3-0.4	10-15	1119	1.63	0.35	0.07	0.006
8		0.3-0.4	15-20	1088	1.74	0.41	0.04	0.007
9		0.3-0.4	20-30	1131	1.45	0.35	0.06	0.008
10		0.3-0.4	>30	1112	1.63	0.39	0.04	0.009
11		0.4-0.5	<10	1204	1.93	0.55	0.06	0.009
12		0.4-0.5	10-15	1286	1.70	0.37	0.04	0.010
13		0.4-0.5	15-20	1309	1.49	0.38	0.06	0.016
14		0.4-0.5	20-30	1117	1.38	0.32	0.04	0.021
15		0.4-0.5	>30	1228	1.42	0.31	0.02	0.027
16		0.5-0.6	<10	1266	1.46	0.32	0.11	0.036
17		0.5-0.6	10-15	1216	1.56	0.38	0.07	0.045
18		0.5-0.6	15-20	1092	1.51	0.40	0.06	0.053
19		0.5-0.6	20-30	1119	1.53	0.37	0.05	0.056
20		0.5-0.6	>30	1200	1.77	0.44	0.06	0.061
21		>0.6	<10	1092	1.83	0.45	0.08	0.063
22		>0.6	10-15	1136	1.71	0.49	0.07	0.066
23		>0.6	15-20	1254	1.68	0.38	0.05	0.069
24		>0.6	20-30	1146	1.49	0.39	0.05	0.075
25		>0.6	>30	1245	1.53	0.37	0.04	0.084
1	Natural forest soil (*F. orientalis*)	<0.3	<10	1213	1.80	0.53	0.33	0.001
2		<0.3	10-15	1145	1.80	0.50	0.37	0.001
3		<0.3	15-20	1047	1.90	0.61	0.32	0.002
4		<0.3	20-30	1232	1.80	0.58	0.35	0.002
5		<0.3	>30	1163	1.76	0.62	0.26	0.003
6		0.3-0.4	<10	1070	1.85	0.51	0.28	0.003
7		0.3-0.4	10-15	1081	1.77	0.62	0.39	0.003
8		0.3-0.4	15-20	1170	1.85	0.52	0.34	0.004
9		0.3-0.4	20-30	1245	1.62	0.52	0.27	0.004

10		0.3-0.4	>30	1107	1.87	0.52	0.31	0.005
11		0.4-0.5	<10	1168	1.72	0.53	0.20	0.005
12		0.4-0.5	10-15	1091	1.76	0.63	0.32	0.006
13		0.4-0.5	15-20	1102	1.93	0.55	0.39	0.006
14		0.4-0.5	20-30	1179	1.80	0.51	0.22	0.007
15		0.4-0.5	>30	1122	1.63	0.48	0.20	0.007
16		0.5-0.6	<10	1203	2.01	0.58	0.27	0.008
17		0.5-0.6	10-15	1204	1.45	0.38	0.29	0.009
18		0.5-0.6	15-20	1318	1.48	0.32	0.25	0.009
19		0.5-0.6	20-30	1180	1.99	0.62	0.26	0.010
20		0.5-0.6	>30	1213	1.95	0.58	0.29	0.015
21		>0.6	<10	1181	1.73	0.58	0.27	0.019
22		>0.6	10-15	1109	1.72	0.38	0.36	0.026
23		>0.6	15-20	1223	1.56	0.32	0.32	0.029
24		>0.6	20-30	1073	1.77	0.62	0.30	0.037
25		>0.6	>30	1231	1.98	0.58	0.27	0.045
1	Natural forest soil (*A. subcordata*)	<0.3	<10	971	2.35	0.78	0.30	0.001
2		<0.3	10-15	1118	2.07	0.79	0.29	0.001
3		<0.3	15-20	959	2.12	0.82	0.29	0.001
4		<0.3	20-30	1100	2.35	0.91	0.27	0.002
5		<0.3	>30	1162	1.93	0.63	0.31	0.002
6		0.3-0.4	<10	1070	2.05	0.60	0.33	0.003
7		0.3-0.4	10-15	1079	1.82	0.67	0.33	0.003
8		0.3-0.4	15-20	1051	2.19	0.68	0.32	0.004
9		0.3-0.4	20-30	1060	2.07	0.72	0.25	0.004
10		0.3-0.4	>30	1070	2.06	0.61	0.27	0.004
11		0.4-0.5	<10	1104	1.74	0.58	0.31	0.005
12		0.4-0.5	10-15	1037	2.16	0.69	0.28	0.006
13		0.4-0.5	15-20	1039	1.72	0.55	0.34	0.006
14		0.4-0.5	20-30	995	1.92	0.71	0.24	0.007
15		0.4-0.5	>30	1059	1.86	0.65	0.26	0.007
16		0.5-0.6	<10	1140	2.02	0.72	0.21	0.008
17		0.5-0.6	10-15	1169	1.80	0.62	0.25	0.009
18		0.5-0.6	15-20	1044	2.00	0.62	0.37	0.009

19		0.5-0.6	20-30	1179	1.84	0.62	0.31	0.009
20		0.5-0.6	>30	1230	1.99	0.62	0.27	0.010
21		>0.6	<10	1081	2.04	0.68	0.29	0.019
22		>0.6	10-15	1279	1.71	0.48	0.27	0.026
23		>0.6	15-20	1260	1.55	0.42	0.26	0.029
24		>0.6	20-30	993	1.86	0.72	0.26	0.032
25		>0.6	>30	996	2.20	0.68	0.30	0.037
1	Natural forest soil (*B. plumose*)	<0.3	<10	1273	1.77	0.50	0.19	0.001
2		<0.3	10-15	1135	1.76	0.54	0.21	0.002
3		<0.3	15-20	1118	2.19	0.74	0.22	0.002
4		<0.3	20-30	961	2.08	0.83	0.27	0.002
5		<0.3	>30	1181	1.75	0.55	0.20	0.003
6		0.3-0.4	<10	1216	1.74	0.52	0.19	0.004
7		0.3-0.4	10-15	1200	1.93	0.59	0.20	0.005
8		0.3-0.4	15-20	1070	1.74	0.60	0.22	0.006
9		0.3-0.4	20-30	1223	1.79	0.64	0.20	0.006
10		0.3-0.4	>30	1149	1.82	0.53	0.19	0.006
11		0.4-0.5	<10	1105	1.78	0.50	0.14	0.007
12		0.4-0.5	10-15	1160	1.86	0.55	0.17	0.008
13		0.4-0.5	15-20	1176	1.73	0.58	0.13	0.008
14		0.4-0.5	20-30	1174	1.89	0.62	0.12	0.009
15		0.4-0.5	>30	1144	1.68	0.54	0.11	0.009
16		0.5-0.6	<10	1195	1.96	0.64	0.23	0.014
17		0.5-0.6	10-15	1168	1.67	0.54	0.21	0.017
18		0.5-0.6	15-20	1091	1.85	0.54	0.23	0.021
19		0.5-0.6	20-30	1224	1.88	0.54	0.18	0.026
20		0.5-0.6	>30	1209	1.93	0.54	0.20	0.030
21		>0.6	<10	1224	1.90	0.60	0.22	0.037
22		>0.6	10-15	1224	1.50	0.40	0.23	0.039
23		>0.6	15-20	1243	1.43	0.34	0.22	0.044
24		>0.6	20-30	1140	1.97	0.64	0.22	0.052
25		>0.6	>30	1220	1.86	0.60	0.15	0.059
1	Natural forest soil (*G. caspica*)	<0.3	<10	1164	1.76	0.52	0.06	0.002
2		<0.3	10-15	1241	2.01	0.56	0.04	0.002

3		<0.3	15-20	996	1.95	0.76	0.05	0.003
4		<0.3	20-30	1088	2.26	0.85	0.07	0.003
5		<0.3	>30	1247	1.82	0.57	0.09	0.004
6		0.3-0.4	<10	1132	1.96	0.54	0.11	0.005
7		0.3-0.4	10-15	1024	2.06	0.61	0.05	0.007
8		0.3-0.4	15-20	1019	2.04	0.62	0.04	0.007
9		0.3-0.4	20-30	1193	1.93	0.66	0.04	0.008
10		0.3-0.4	>30	1157	1.80	0.55	0.04	0.009
11		0.4-0.5	<10	1082	1.79	0.51	0.05	0.009
12		0.4-0.5	10-15	1129	1.68	0.55	0.02	0.010
13		0.4-0.5	15-20	1130	1.84	0.66	0.02	0.015
14		0.4-0.5	20-30	1214	1.94	0.61	0.06	0.019
15		0.4-0.5	>30	1057	1.82	0.52	0.02	0.025
16		0.5-0.6	<10	1053	2.16	0.66	0.00	0.030
17		0.5-0.6	10-15	1137	1.83	0.56	-0.01	0.038
18		0.5-0.6	15-20	1070	1.70	0.56	0.05	0.045
19		0.5-0.6	20-30	1062	1.81	0.56	0.06	0.048
20		0.5-0.6	>30	1087	1.95	0.56	0.04	0.051
21		>0.6	<10	1188	2.07	0.62	0.04	0.058
22		>0.6	10-15	1240	1.77	0.42	0.05	0.064
23		>0.6	15-20	1246	1.44	0.36	0.04	0.066
24		>0.6	20-30	1156	2.05	0.66	0.06	0.071
25		>0.6	>30	1074	2.03	0.62	0.07	0.080
1	Natural forest soil (*S. ebulus*)	<0.3	<10	1183	1.73	0.45	0.07	0.002
2		<0.3	10-15	1114	1.81	0.49	0.04	0.002
3		<0.3	15-20	1199	2.03	0.69	0.10	0.002
4		<0.3	20-30	1017	2.15	0.78	0.07	0.003
5		<0.3	>30	1236	1.88	0.50	0.06	0.003
6		0.3-0.4	<10	1072	1.58	0.47	0.06	0.004
7		0.3-0.4	10-15	1226	1.66	0.54	0.06	0.006
8		0.3-0.4	15-20	1256	1.89	0.55	0.09	0.006
9		0.3-0.4	20-30	1065	1.71	0.59	0.07	0.007
10		0.3-0.4	>30	1241	1.68	0.48	0.04	0.008
11		0.4-0.5	<10	1142	1.69	0.49	0.10	0.008

12		0.4-0.5	10-15	1212	1.88	0.56	0.02	0.009
13		0.4-0.5	15-20	1184	1.93	0.59	0.06	0.009
14		0.4-0.5	20-30	1133	1.80	0.51	0.07	0.010
15		0.4-0.5	>30	1135	1.84	0.49	0.02	0.017
16		0.5-0.6	<10	1182	2.05	0.59	0.05	0.024
17		0.5-0.6	10-15	1099	1.79	0.47	0.05	0.029
18		0.5-0.6	15-20	1229	1.64	0.49	0.04	0.033
19		0.5-0.6	20-30	1153	1.77	0.49	0.08	0.039
20		0.5-0.6	>30	1129	1.63	0.49	0.08	0.044
21		>0.6	<10	1084	1.81	0.55	0.07	0.052
22		>0.6	10-15	1127	1.39	0.31	0.09	0.056
23		>0.6	15-20	1152	1.49	0.29	0.10	0.059
24		>0.6	20-30	1044	2.09	0.69	0.06	0.062
25		>0.6	>30	1170	1.73	0.55	0.06	0.071
1	Planted forest soil (*Q. castaneifolia*)	<0.3	<10	1285	0.82	0.41	0.32	0.002
2		<0.3	10-15	1283	0.73	0.41	0.48	0.002
3		<0.3	15-20	1289	0.70	0.46	0.22	0.002
4		<0.3	20-30	1279	0.65	0.49	0.29	0.003
5		<0.3	>30	1275	0.71	0.53	0.25	0.003
6		0.3-0.4	<10	1288	0.69	0.47	0.20	0.005
7		0.3-0.4	10-15	1283	0.82	0.43	0.47	0.006
8		0.3-0.4	15-20	1271	0.84	0.35	0.35	0.007
9		0.3-0.4	20-30	1276	0.77	0.33	0.37	0.008
10		0.3-0.4	>30	1285	0.78	0.40	0.32	0.008
11		0.4-0.5	<10	1275	0.84	0.41	0.42	0.009
12		0.4-0.5	10-15	1278	0.86	0.41	0.33	0.010
13		0.4-0.5	15-20	1276	0.84	0.38	0.32	0.012
14		0.4-0.5	20-30	1282	0.78	0.39	0.32	0.016
15		0.4-0.5	>30	1284	0.78	0.35	0.30	0.022
16		0.5-0.6	<10	1275	0.79	0.35	0.33	0.027
17		0.5-0.6	10-15	1282	0.95	0.36	0.50	0.035
18		0.5-0.6	15-20	1286	0.95	0.33	0.35	0.042
19		0.5-0.6	20-30	1287	0.90	0.49	0.22	0.045
20		0.5-0.6	>30	1292	0.88	0.32	0.36	0.049

21		>0.6	<10	1280	0.89	0.51	0.21	0.056
22		>0.6	10-15	1280	0.94	0.40	0.23	0.061
23		>0.6	15-20	1285	0.88	0.25	0.25	0.063
24		>0.6	20-30	1281	0.65	0.18	0.32	0.068
25		>0.6	>30	1289	0.69	0.52	0.48	0.077
1	Planted forest soil (*A. glutinosa*)	<0.3	<10	1268	0.78	0.52	0.41	0.001
2		<0.3	10-15	1269	0.83	0.54	0.47	0.001
3		<0.3	15-20	1255	0.94	0.49	0.51	0.002
4		<0.3	20-30	1265	1.02	0.49	0.42	0.002
5		<0.3	>30	1274	0.77	0.52	0.52	0.003
6		0.3-0.4	<10	1275	0.95	0.51	0.45	0.004
7		0.3-0.4	10-15	1284	0.94	0.52	0.51	0.005
8		0.3-0.4	15-20	1265	0.77	0.43	0.45	0.005
9		0.3-0.4	20-30	1266	0.96	0.61	0.51	0.006
10		0.3-0.4	>30	1285	0.94	0.52	0.46	0.006
11		0.4-0.5	<10	1265	0.94	0.62	0.52	0.007
12		0.4-0.5	10-15	1284	0.94	0.52	0.51	0.008
13		0.4-0.5	15-20	1268	0.92	0.51	0.50	0.008
14		0.4-0.5	20-30	1288	0.88	0.44	0.48	0.009
15		0.4-0.5	>30	1284	0.92	0.41	0.47	0.009
16		0.5-0.6	<10	1288	0.82	0.51	0.48	0.011
17		0.5-0.6	10-15	1266	0.88	0.52	0.50	0.014
18		0.5-0.6	15-20	1221	0.89	0.52	0.49	0.018
19		0.5-0.6	20-30	1262	0.92	0.49	0.52	0.023
20		0.5-0.6	>30	1268	0.94	0.50	0.51	0.027
21		>0.6	<10	1269	0.95	0.55	0.48	0.035
22		>0.6	10-15	1289	0.87	0.55	0.39	0.036
23		>0.6	15-20	1266	0.87	0.49	0.38	0.041
24		>0.6	20-30	1265	0.82	0.59	0.48	0.049
25		>0.6	>30	1274	0.83	0.48	0.40	0.057
1	Planted forest soil (*Z. carpinifolia*)	<0.3	<10	1281	0.71	0.52	0.25	0.001
2		<0.3	10-15	1256	0.90	0.42	0.36	0.001
3		<0.3	15-20	1275	0.77	0.44	0.44	0.002
4		<0.3	20-30	1269	0.77	0.40	0.36	0.002

5		<0.3	>30	1289	0.80	0.41	0.23	0.003
6		0.3-0.4	<10	1281	0.90	0.51	0.36	0.004
7		0.3-0.4	10-15	1274	0.90	0.41	0.21	0.006
8		0.3-0.4	15-20	1275	0.87	0.35	0.23	0.006
9		0.3-0.4	20-30	1266	0.72	0.32	0.44	0.006
10		0.3-0.4	>30	1285	0.65	0.42	0.46	0.007
11		0.4-0.5	<10	1284	0.82	0.44	0.35	0.008
12		0.4-0.5	10-15	1285	0.81	0.43	0.38	0.009
13		0.4-0.5	15-20	1283	0.78	0.47	0.41	0.009
14		0.4-0.5	20-30	1271	0.78	0.38	0.26	0.010
15		0.4-0.5	>30	1265	0.73	0.35	0.29	0.015
16		0.5-0.6	<10	1288	0.75	0.42	0.48	0.021
17		0.5-0.6	10-15	1271	0.65	0.41	0.28	0.026
18		0.5-0.6	15-20	1271	0.95	0.33	0.49	0.031
19		0.5-0.6	20-30	1214	0.69	0.49	0.44	0.036
20		0.5-0.6	>30	1285	0.67	0.31	0.36	0.041
21		>0.6	<10	1275	0.95	0.31	0.48	0.049
22		>0.6	10-15	1269	0.93	0.43	0.30	0.053
23		>0.6	15-20	1255	0.78	0.25	0.30	0.056
24		>0.6	20-30	1265	0.82	0.32	0.21	0.059
25		>0.6	>30	1282	0.79	0.41	0.24	0.068
1	Deforested soil + application of rice husk biochar	<0.3	<10	1432	2.14	0.81	0.57	0.008
2		<0.3	10-15	1452	1.89	0.59	0.43	0.015
3		<0.3	15-20	1398	2.21	0.87	0.47	0.018
4		<0.3	20-30	1367	1.98	0.61	0.52	0.022
5		<0.3	>30	1466	2.36	0.94	0.79	0.029
6		0.3-0.4	<10	1487	2.45	1.07	0.69	0.013
7		0.3-0.4	10-15	1421	1.85	0.53	0.51	0.017
8		0.3-0.4	15-20	1416	1.74	0.48	0.60	0.026
9		0.3-0.4	20-30	1412	2.27	0.80	0.83	0.031
10		0.3-0.4	>30	1417	2.29	0.87	0.50	0.038
11		0.4-0.5	<10	1495	2.35	0.84	0.65	0.014
12		0.4-0.5	10-15	1435	1.97	0.66	0.36	0.020
13		0.4-0.5	15-20	1456	1.85	0.55	0.35	0.029

14		0.4-0.5	20-30	1444	2.19	0.87	0.54	0.035
15		0.4-0.5	>30	1425	2.14	0.70	0.42	0.039
16		0.5-0.6	<10	1422	2.17	0.74	0.51	0.022
17		0.5-0.6	10-15	1436	2.36	1.01	0.54	0.032
18		0.5-0.6	15-20	1355	1.59	0.39	0.53	0.038
19		0.5-0.6	20-30	1462	2.03	0.67	0.56	0.045
20		0.5-0.6	>30	1361	2.65	1.25	0.46	0.051
21		>0.6	<10	1422	2.57	1.02	0.89	0.029
22		>0.6	10-15	1411	1.98	0.60	0.94	0.036
23		>0.6	15-20	1319	1.84	0.60	0.58	0.044
24		>0.6	20-30	1325	2.23	0.81	0.84	0.052
25		>0.6	>30	1439	2.41	0.96	0.36	0.059
1	Deforested soil + inoculation with *Bacillus subtilis OSU 142*	<0.3	<10	1281	2.42	1.06	0.45	0.009
2		<0.3	10-15	1321	2.22	0.87	0.48	0.011
3		<0.3	15-20	1312	2.26	0.82	0.50	0.016
4		<0.3	20-30	1272	2.46	0.92	0.37	0.021
5		<0.3	>30	1310	2.27	0.95	0.42	0.025
6		0.3-0.4	<10	1260	2.52	0.98	0.37	0.013
7		0.3-0.4	10-15	1350	2.07	0.78	0.47	0.018
8		0.3-0.4	15-20	1311	2.27	0.94	0.47	0.022
9		0.3-0.4	20-30	1311	2.27	0.83	0.43	0.027
10		0.3-0.4	>30	1351	2.07	0.78	0.40	0.032
11		0.4-0.5	<10	1257	2.54	1.04	0.41	0.017
12		0.4-0.5	10-15	1254	2.55	1.09	0.45	0.022
13		0.4-0.5	15-20	1369	1.98	0.70	0.40	0.026
14		0.4-0.5	20-30	1387	1.89	0.57	0.44	0.033
15		0.4-0.5	>30	1395	1.85	0.56	0.38	0.035
16		0.5-0.6	<10	1272	2.46	0.94	0.30	0.024
17		0.5-0.6	10-15	1323	2.21	0.88	0.40	0.032
18		0.5-0.6	15-20	1321	2.22	0.83	0.33	0.036
19		0.5-0.6	20-30	1325	2.20	0.80	0.33	0.039
20		0.5-0.6	>30	1318	2.23	0.84	0.33	0.047
21		>0.6	<10	1314	2.25	0.86	0.50	0.028
22		>0.6	10-15	1258	2.53	1.13	0.22	0.038

23		>0.6	15-20	1347	2.09	0.67	0.33	0.046
24		>0.6	20-30	1349	2.08	0.80	0.34	0.052
25		>0.6	>30	1363	2.01	0.70	0.31	0.063
1	Deforested soil + inoculation with *Bacillus polymyxa strain BcP26* and planting of *Zoysia* grass seeds	<0.3	<10	1030	2.24	0.78	0.78	0.004
2		<0.3	10-15	1164	2.23	0.71	0.76	0.010
3		<0.3	15-20	953	2.31	0.81	0.77	0.013
4		<0.3	20-30	1088	2.20	0.87	0.76	0.020
5		<0.3	>30	1060	2.05	0.87	0.77	0.023
6		0.3-0.4	<10	1038	2.28	0.81	0.83	0.007
7		0.3-0.4	10-15	1016	2.17	0.88	0.87	0.013
8		0.3-0.4	15-20	1025	2.33	0.89	0.79	0.020
9		0.3-0.4	20-30	1213	1.71	0.51	0.56	0.022
10		0.3-0.4	>30	1155	2.02	0.81	0.71	0.025
11		0.4-0.5	<10	1036	2.32	0.79	0.69	0.010
12		0.4-0.5	10-15	1100	2.50	0.89	0.89	0.018
13		0.4-0.5	15-20	1087	2.07	0.85	0.78	0.025
14		0.4-0.5	20-30	1004	2.06	0.76	0.73	0.027
15		0.4-0.5	>30	1068	2.10	0.77	0.70	0.029
16		0.5-0.6	<10	934	2.12	0.85	0.72	0.013
17		0.5-0.6	10-15	971	2.22	0.86	0.86	0.021
18		0.5-0.6	15-20	989	2.46	0.89	0.81	0.026
19		0.5-0.6	20-30	1109	2.08	0.61	0.60	0.031
20		0.5-0.6	>30	1132	1.74	0.63	0.64	0.036
21		>0.6	<10	1159	1.91	0.52	0.61	0.021
22		>0.6	10-15	1106	2.08	0.65	0.69	0.024
23		>0.6	15-20	1144	2.19	0.74	0.73	0.029
24		>0.6	20-30	1165	2.20	0.76	0.69	0.033
25		>0.6	>30	959	2.36	0.81	0.72	0.039
1	Deforested soil + hydromulching using *Zoysia* grass seed and addition of silica nanoparticles	<0.3	<10	1154	2.23	0.81	0.73	0.003
2		<0.3	10-15	1049	2.07	0.87	0.74	0.009
3		<0.3	15-20	1038	2.16	0.87	0.86	0.011
4		<0.3	20-30	1020	1.97	0.81	0.71	0.018
5		<0.3	>30	1057	2.25	0.88	0.86	0.021
6		0.3-0.4	<10	975	2.14	0.89	0.87	0.006

7		0.3-0.4	10-15	1049	2.23	0.71	0.70	0.012
8		0.3-0.4	15-20	1000	2.16	0.81	0.75	0.017
9		0.3-0.4	20-30	1129	1.77	0.61	0.59	0.021
10		0.3-0.4	>30	1153	1.74	0.59	0.62	0.023
11		0.4-0.5	<10	1106	2.26	0.86	0.77	0.009
12		0.4-0.5	10-15	1141	2.21	0.85	0.73	0.015
13		0.4-0.5	15-20	1150	2.12	0.74	0.71	0.023
14		0.4-0.5	20-30	1152	1.97	0.71	0.74	0.027
15		0.4-0.5	>30	1115	1.81	0.65	0.61	0.028
16		0.5-0.6	<10	1193	1.62	0.47	0.55	0.012
17		0.5-0.6	10-15	994	2.09	0.71	0.65	0.021
18		0.5-0.6	15-20	1235	2.01	0.62	0.68	0.023
19		0.5-0.6	20-30	1095	1.78	0.52	0.60	0.030
20		0.5-0.6	>30	1144	1.88	0.59	0.62	0.034
21		>0.6	<10	1218	2.04	0.58	0.65	0.020
22		>0.6	10-15	1020	2.07	0.64	0.64	0.023
23		>0.6	15-20	1068	1.95	0.72	0.73	0.027
24		>0.6	20-30	1181	1.88	0.69	0.66	0.031
25		>0.6	>30	1160	1.85	0.71	0.66	0.038
1	Deforested soil, hydromulching using *Zoysia* grass seed	<0.3	<10	1194	1.68	0.54	0.56	0.013
2		<0.3	10-15	1201	1.81	0.51	0.58	0.018
3		<0.3	15-20	1195	2.01	0.61	0.60	0.027
4		<0.3	20-30	1068	1.70	0.55	0.56	0.036
5		<0.3	>30	1111	2.03	0.58	0.67	0.044
6		0.3-0.4	<10	1194	1.73	0.55	0.59	0.018
7		0.3-0.4	10-15	1091	1.82	0.61	0.64	0.026
8		0.3-0.4	15-20	1207	1.95	0.59	0.57	0.039
9		0.3-0.4	20-30	1330	1.41	0.36	0.51	0.048
10		0.3-0.4	>30	1211	1.57	0.48	0.57	0.059
11		0.4-0.5	<10	1095	1.97	0.76	0.79	0.024
12		0.4-0.5	10-15	1054	2.13	0.66	0.72	0.038
13		0.4-0.5	15-20	1239	1.65	0.52	0.61	0.063
14		0.4-0.5	20-30	1248	1.42	0.31	0.42	0.069
15		0.4-0.5	>30	1185	2.00	0.62	0.60	0.087

16		0.5-0.6	<10	1082	1.75	0.48	0.50	0.034
17		0.5-0.6	10-15	1248	1.68	0.56	0.63	0.059
18		0.5-0.6	15-20	1222	1.84	0.54	0.54	0.075
19		0.5-0.6	20-30	1221	1.70	0.38	0.44	0.081
20		0.5-0.6	>30	1214	1.77	0.44	0.49	0.086
21		>0.6	<10	1115	1.90	0.62	0.67	0.041
22		>0.6	10-15	1145	1.88	0.55	0.61	0.066
23		>0.6	15-20	1136	1.67	0.52	0.57	0.082
24		>0.6	20-30	1278	1.79	0.48	0.56	0.088
25		>0.6	>30	1086	1.68	0.43	0.47	0.079
1	Deforested soil	<0.3	<10	1591	1.83	0.59	0.28	0.015
2		<0.3	10-15	1526	1.72	0.46	0.13	0.016
3		<0.3	15-20	1579	1.81	0.58	0.18	0.022
4		<0.3	20-30	1572	1.69	0.44	0.35	0.029
5		<0.3	>30	1594	1.82	0.55	0.41	0.039
6		0.3-0.4	<10	1596	1.82	0.57	0.32	0.019
7		0.3-0.4	10-15	1594	1.75	0.51	0.27	0.024
8		0.3-0.4	15-20	1536	1.68	0.46	0.29	0.034
9		0.3-0.4	20-30	1545	1.85	0.60	0.28	0.061
10		0.3-0.4	>30	1532	1.87	0.64	0.23	0.067
11		0.4-0.5	<10	1554	1.77	0.55	0.28	0.020
12		0.4-0.5	10-15	1591	1.69	0.42	0.27	0.029
13		0.4-0.5	15-20	1569	1.65	0.45	0.25	0.039
14		0.4-0.5	20-30	1531	1.69	0.42	0.23	0.067
15		0.4-0.5	>30	1511	1.78	0.56	0.23	0.072
16		0.5-0.6	<10	1581	1.72	0.52	0.24	0.028
17		0.5-0.6	10-15	1536	1.71	0.51	0.18	0.036
18		0.5-0.6	15-20	1559	1.86	0.57	0.14	0.059
19		0.5-0.6	20-30	1576	1.65	0.43	0.31	0.071
20		0.5-0.6	>30	1585	1.75	0.45	0.39	0.079
21		>0.6	<10	1586	1.85	0.57	0.37	0.037
22		>0.6	10-15	1589	1.73	0.50	0.24	0.051
23		>0.6	15-20	1539	1.66	0.45	0.30	0.071
24		>0.6	20-30	1575	1.81	0.53	0.31	0.077

25		>0.6	>30	1578	1.91	0.60	0.20	0.091