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Plot-Scale Effects of Ground-Based Skidding on Runoff and Soil Loss in Relation to Slopes and Leaf-On and Leaf-Off Periods in the Mixed Broadleaf Forests

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Abstract

Soil compaction and loss of surface litter from skid trails reduced the water absorption capacity in mineral soils, which reduced water infiltration and increased runoff, which then caused surface erosion. The hypothesis was that ground-based skidding, different slope gradient classes (0–20% and 20–40%), and forest canopy cover (leaf-on and leaf-off period) would be significantly effect on runoff and sediment loss. In order to measure the total runoff and the sediment loss, quadruplicate bounded runoff plot (2 m^2) was established on the skidding and the control sites, and two different slope angle classes on each site (totally 16 runoff plots with 20 rainfall events) in the Gorazbon district in Hyrcanian deciduous forests following Timberjack 450C skidding operations (32 machine passes) over one-year. The natural rainfalls were measured due to get more useful data. The skidding and the leaf-on and leaf-off period had statistically significant effects on runoff and sediments ($P < 0.05$). There was a statistically significant difference between runoff and sediment loss in different leaf-on and leaf-off periods, with leaf-off period having the highest sediment loss, while the leaf-on period had the least. The slope angle classes and its interactions had no significant effect on runoff and sediment loss. The highest runoff of just over 1.6 mm was from a skid trail with a 20–40% slope in the leaf-off period, and the highest sediment production was 6.95 g in the skid trail with a 20–40% slope in the leaf-off period. In the Hyrcanian deciduous forest, fallen leaves (leaf-off period) were coincided with the highest and most erosive rainfall, which resulted in an increase in runoff and sediment yield.

Keywords: Skidding, Runoff, Soil loss, Leaf cover period, Slope gradients

1. Introduction

Forest soil infiltration rates are generally very high and runoff exceptionally happens in forest stands due to presence of litter layer (Stuart and Edwards, 2006; Jourgholami et al., 2018a, b). By applying pressure on soil, macro-pores decreases, which results in an increase of soil bulk density (Jourgholami et al., 2014; Grace et al., 2006; Jourgholami et al., 2019a, b) and a reduction of the total porosity due primarily to the loss of macropores (Majnounian and Jourgholami, 2013). This decreases the saturated hydraulic conductivity and soil infiltration capacity (Greacen and Sands, 1980; Moore and Wondzell, 2005; Grace et al., 2006; Cambi et al., 2015), which can result in surface runoff when the rainfall intensity exceeds the infiltration rate (MacDonald and Stednick, 2003). Litter cover is one of the most important factors controlling surface erosion in forests (Sosa-Pérez and MacDonald, 2017a). A litter layer absorbs the kinetic energy of raindrops, since; the litter layer protects soil from rainsplash and sealing (Sosa-Pérez and MacDonald, 2017b). The litter also supplies organic matter and nutrients for soil organisms (Brown et al., 2005; Holz et al., 2015), and both the organic matter and the organisms can increase infiltration rates (MacDonald and Stednick, 2003). Typically, about 10-25% of the rain falling onto a canopy will be intercepted by the foliage (Moore and Wondzell, 2005).

Leaf litter layer shields the soil surface, thus mitigating soil detachment, and providing ground roughness that slow the surface velocities and trap the soil particle from moving down the slope (Hartanto et al., 2003). Previous studies have demonstrated that machine operating trails can result in a considerable source of soil loss (Hartanto et al., 2003; Forsyth et al., 2006; Holz et al., 2015; Jourgholami et al., 2019a, b). Several studies have also indicated that the reduction of canopy cover by logging operations enhances the overland flow and soil loss, resulting in changes in stream flow patterns (Wade et al., 2012; Webb et al., 2012; Wagenbrenner and Robichaud, 2014; Holz et al., 2015). In the Caspian forests in the north of Iran, Jourgholami and Etehadi Abari (2017a) found that the runoff and sediment in the skid trail plots (8 m^2) were 1.62 mm and 0.079 kg m^2.

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Soil erosion measuring can be conducted both at plot level and at catchment levels, with upslope or on-site monitoring being relatively simple and inexpensive to conduct (Hartanto et al., 2003). In this study, the surface runoff and its sediment material were monitored from skid trails and control areas in Gorazbon district in the Hyrcanian deciduous forest. The objective of the study was to assess the runoff and sediment production from compacted skid trail and the control plots from rainfall over one year. It was hypothesized that treat (the skid trail and the control plots), trail gradient, and foliage (leaf-on and leaf-off period) have a significant effect on runoff and soil loss.

2. Material and Methods

2.1. Study Area

This study was conducted in the compartments no. 317 and no. 318 of the Gorazbon district in Kheyrud Forest (Forest Research Station, University of Tehran) in the Caspian forest region (Figure 1). These compartments ranged in altitudes from m above sea level on the southern aspect. The study site had an altitude ranging from 1160 m to 1210 m a.s.l. and the mean annual precipitation was 1260 mm, with the highest in October and lowest in July. The climate of the study area was humid and mean annual temperature was 12.8 °C, with the hottest in July (25 °C) and coldest in December (0 °C). According to the USDA soil taxonomy, the soils are Alfisols and the soil texture was classified as silt loam to loamy from limestone. The study area is a part of the Hyrcanian forests, which is a natural deciduous uneven-aged forest dominated with species such as beech (*Fagus orientalis* Lipsky), hornbeam (*Carpinus betulus* L.), and Caucasian alder (*Alnus subcordata* C. A. Mey) with tree mixture of stands were 49, 41, and 10%, respectively. These forests were managed with the group selection and the single-tree selection.

The average growing stock in the compartments no. 317 and 318 were 520 m^3ha^{-1} and 470 m^3 ha^{-1}, respectively. Mean diameter was 44 cm and mean height of stand was 26 m. Thickness of the litter on the forest floor was 4.1 cm. The forest floor litter type was mull.

The felling of marked trees in the compartment no. 317 was conducted in March 2014 and the skidding was carried out in August (Jourgholami and Etehadi Abari, 2017b). At the time of skidding operations, the weather was very dry and warm. A 4WD Timberjack 450C rubber-tired skidder was used for timber extraction, weighing of 10.3 tons, and the average log volume was 3.5 cubic meters per turn.

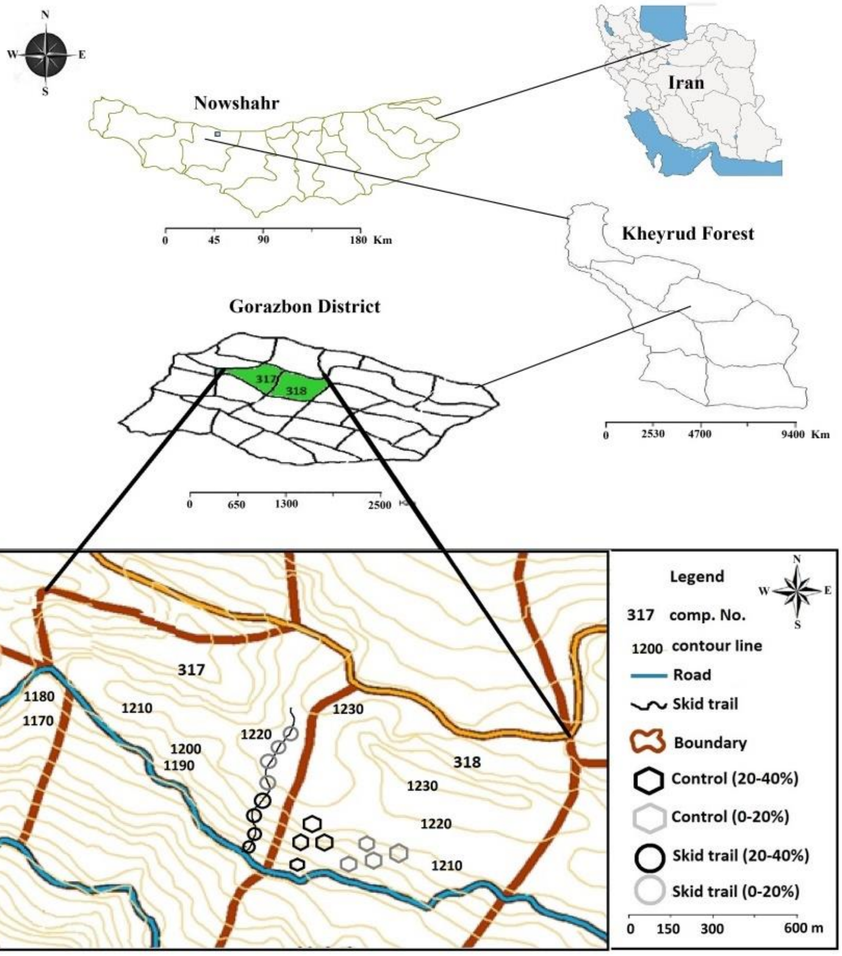

Figure 1. Layout of the skid trails and the control sample plot in the Gorazbon district in the Hyrcanian forest

2.2. Experimental Design

In order to measure runoff, total 16 plots were installed in the two compartments, with eight on the skid trails in the compartment no. 317 and eight in an undisturbed area (control area) in the compartment no. 318. The skid trail and the control areas were about 300 m apart and had similar environmental characteristics (Jourgholami et al., 2019a). The eight plots were also divided into two groups and each plot had two slope classes: 0–20% and 20–40%. The skid trail plots did not have any lateral slope. In each sample plot, the canopy cover, litter depth, soil bulk density, total porosity and organic matter were determined (Table 1). Soil organic C was measured using the Walkley-Black method (Walkley and Black, 1934). Soil bulk density was measured by using a metal ring pressed into the soil, 40 mm long and 56 mm in diameter. Then, the soil samples were dried in an oven at 105°C (24 h). Soil bulk density was calculated using Eq. (1):

$$\mathrm{Db} = \frac{\mathrm{Wd}}{VC} \tag{1}$$

Db = soil bulk density
Wd = weight of the dry soil (g)
VC = volume of the soil cores

The ASTM D854-00 2000 standard was used to measure the soil particle density and to calculate total porosity, the formula as (TP = [1 - (d_s/d_p)] × 100) was used (Jourgholami et al., 2018a). An ocular observation was conducted to predict the canopy cover. Litter depth was determined using a tape measure.

2.3. Measurements

The present study was carried out in November 2014 through in September 2015. The forest had both a leaf-off period (November 24, 2014 to April 12, 2015) and a leaf-on period (from April 12, 2015 to September 18, 2015). The plots were 2 m length by 1 m width (Figure 1). Each plot was bordered by metal strips sunk 20 cm into the ground, and the strips extended about 15 cm upper the surface to prohibit inflows. A flexible tube drainage outlet was applied to convey the surface flow to a 0.04 m^3 tank (Jourgholami et al., 2018a). A storm event was considered to be a sample (rainfall) that was at least 8 hours interval from the previous rainfall, and then each rainfall may have been incorporated with the some storm events. After mixing the sored runoff and sediments, the tanks were emptied and cleaned to ensure that there was no residual sediment. After each event, the runoff volume was measured, filtered, oven-dried at 105°C, and weighed to determine the sediment yield (Jourgholami et al., 2019a). To measure the amount of rainfall at the study site in the skid trail and the control area, two standard rain gauges were used, less than 100 m away from the runoff plots. Over the period of study, 20 runoff events were measured.

2.4. Statistical analysis

A completely randomized design was applied whereby the plots were randomly assigned for the treat, trail gradient and foliage (Leaf-off period; leaf-on period). The normal distribution of data was checked with the use of the Kolmogorov–Smirnov test. Levene's test was conducted for testing the homogeneity of variance among treatments. To compare runoff and sediment among the treatments (cover, slope gradient and season), a two-way analysis of variance (ANOVA) was performed. Duncan's Multiple Range tests were applied to differences among treat, trail gradient, and foliage (Leaf-off period; Leaf-on period) treatment means at $P \leq 0.05$, after founding significant differences among treatments by the ANOVA. To examine the relationships among runoff, sediment and the rainfall for the two treatments (the skid trail and the control area) on the leaf-off and leaf-on period, the regression analysis was conducted. The SPSS software was applied to conduct all the statistical analyses (release 17.0; SPSS, Chicago, IL, USA).

3. Results

3.1. Plot characteristics and Rainfall

The 0–20% slope class included the trail sections that ranged from 7% to 16% in slope, whereas the slopes in the 20-40% slope class ranged from 22–34%. The measured traffic volumes were 32 passes for the traffic on the sample plots. The different soil properties, litter depth and canopy cover at the study sites are shown in Table 1. Soil bulk density for the control plots (1.09-1.10 g cm^{-3}) was significantly lower than the skid trails (1.30-1.35 g cm^{-3}).

Table 1. Mean (±std) bulk density, total porosity, organic matter, litter depth and cover canopy in the two slope classes for the skid trail and the control plots

Treat	Slope (%)	Bulk density (g cm^{-3})	Total Porosity (%)	Organic Matter (%)	Litter depth (cm)	Canopy cover (%)
Control	0-20	1.10(±0.05)^b	58.5(±0.8)^a	11.1(±1.1)^a	3.47(±0.8)^a	87(±4.6)^a
	20-40	1.09(±0.06)^b	58.9(±1.1)^a	10.2(±1.2)^a	3.30(±0.6)^a	85(±3.7)^a
Skid trail	0-20	1.30(±0.11)^a	51.0(±1.2)^b	3.23(±0.3)^b	0.00^b	89(±4.2)^a
	20-40	1.35(±0.14)^a	49.1(±0.7)^b	3.65(±0.5)^b	0.00^b	84(±5.1)^a

Different letters indicate statistically significant differences (α≤0.05) between group means using independent sample t-test

Total porosity for both trail gradient of 0-20% and 20-40% were significantly lower than the control plots (Table 1). The greater amounts of organic matter were found on the control plots (10.2-11.1%), whilst the organic matter was significantly lower on the skid trail (3.23-3.65%). The values of litter depth ranged from 3.30 cm to 3.47 cm on the control plots, while the litter depth was removed from all the gradient classes of skid trails. Canopy covers were not significantly different between the control plots (85-87%) and the skid trails (84-89%). In the measurement period, totally 20 rainfall events were recorded. Amount of rainfall ranged from 3.6 mm to62 mm with an average of 25.85 mm.

3.2. Runoff

The treat ($P \leq 0.01$), the foliage ($P \leq 0.01$), and the interaction effects of the treat × the foliage ($P = 0.011$) had a significant effect on the runoff, but the trail gradient and the interaction of treat × trail gradient, trail gradient × foliage, and treat × trail gradient × foliage had no significant effect on the runoff (all $P >$ 0.05; Table 2).

Amount of runoff for the leaf-off period in the trail gradient of 20-40% and 0-20% were 1.57 mm and 1.34 mm, respectively, while the least amount of runoff was measured on all the gradient groups of the control plots and both the leaf-on and the leaf-off period (Table 3).

Table 2. ANOVA for the effect of treat, trail gradient, foliage variables and its interactions on runoff and sediment

Source	*df*	*F*		*Sig.*	
		Runoff	Sediment	Runoff	Sediment
Treat	1	11.65	3.42	0.001^{**}	0.04^{*}
Trail gradient	1	0.001	1.37	0.975^{ns}	0.24^{ns}
Foliage	1	12.31	3.15	0.001^{**}	0.03^{*}
Treat × Trail gradient	1	0.06	1.32	0.802^{ns}	0.25^{ns}
Treat × Foliage	1	6.57	3.03	0.011^{*}	0.05^{*}
Trail gradient × Foliage	1	0.04	1.47	0.846^{ns}	0.23^{ns}
Treat × Trail gradient × Foliage	1	0.6	1.46	0.441^{ns}	0.22^{ns}

The level of significance of the model is indicated by: $^{*}P < 0.05$; $^{**}P < 0.01$, ^{ns}: not significant $P \geq 0.05$

Table 3. Means (±std) of runoff (mm) and sediment (g) on different trail gradient and foliage

Treatment	Trail gradient	Foliage	Runoff (mm)	Sediment (g)
Control	0-20%	Leaf-on	0.15 ± 0.07^{d}	0.15 ± 0.02^{c}
		Leaf-off	0.43 ± 0.12^{c}	0.18 ± 0.03^{c}
	20-40%	Leaf-on	0.22 ± 0.08^{c}	0.17 ± 0.04^{c}
		Leaf-off	0.28 ± 0.09^{c}	0.22 ± 0.06^{c}
Skid trail	0-20%	Leaf-on	0.40 ± 0.12^{c}	0.34 ± 0.08^{c}
		Leaf-off	1.34 ± 0.24^{a}	1.58 ± 0.42^{b}
	20-40%	Leaf-on	0.28 ± 0.11^{c}	0.23 ± 0.07^{c}
		Leaf-off	1.57 ± 0.35^{a}	6.95 ± 1.23^{a}

Note: Different letters after means within each treatment, trail gradient, and foliage indicate significant differences by Duncan's test ($P < 0.05$)

Regardless of trail gradient and foliage, the runoff for the skid trail plots (0.897 mm) was 2.3 time higher than the control plots (0.271 mm). Trail gradients had no significant effects on runoff for both the skid trail and the control plots. In the skid trail, the runoff in the leaf-off period for trail gradient of 0-20 and 20-40% were 4.6 and 2.4 times higher than the same trail gradient on the leaf-on period. The runoff was highest in the leaf-off period on the skid trail (1.45 mm) followed by the leaf-on period on the skid trail ≈ leaf-off period on the control ≈ leaf-on period on the control (Figure 2). The relation between rainfall and runoff was displayed in the scatter diagram in Figure 3. A linear relationship was observed between runoff and rainfall for both leaf-off and leaf-on period at the skid trail and control plots (Figure 3).

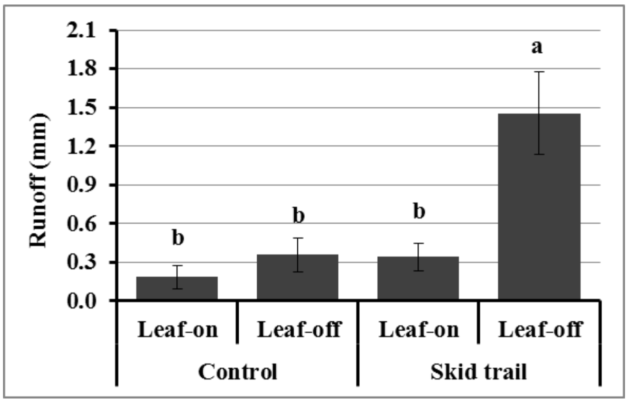

Figure 2. Mean runoff in the skid trail and the control plot during leaf-on and leaf-off period

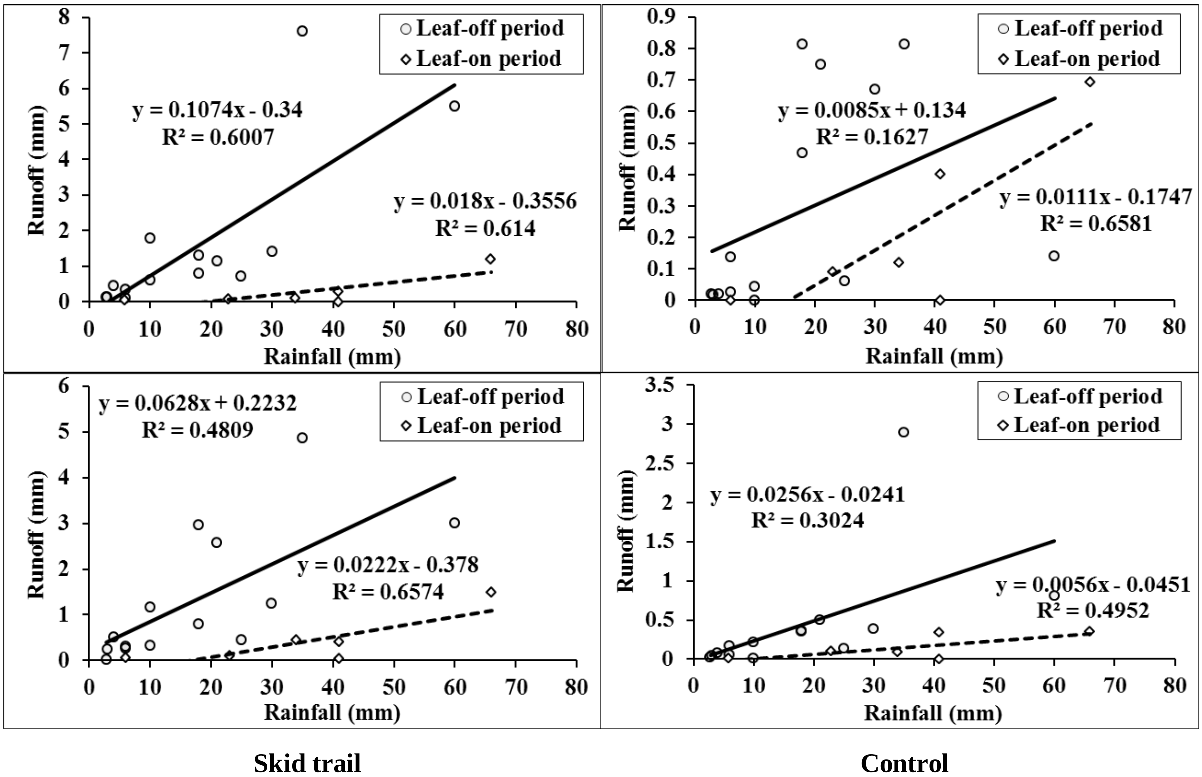

Figure 3. The relationship between runoff and rainfall for each slope gradient class (0–20% and 20–40%) for the skid trail and undisturbed area (control plots) in the treatments including leaf-off period and leaf-on period

3.3. Sediment

Sediment yield were significantly influenced by treat and foliage (all $P \leq 0.05$), as well as the interaction effect of treat × foliage ($P \leq 0.05$), but not the trail gradient and the interaction of treat × trail gradient, trail gradient × foliage, and treat × trail gradient × foliage ear (all $P > 0.05$).

The highest sediment production values of 6.95 and 1.58 g were measured in the leaf-off period at a trail gradient of 0-20 and 20-40% in the skid trail treatment, respectively, while the least values of sediment production were measured on all the gradient classes of control plots. In the skid trail with gradient of 20-40%, the mean sediment production in the leaf-off and leaf-on period were 29.2 and 3.7 times higher than the sediment values of both leaf-off and leaf-on period, respectively. The independent samples t-test indicated that treat (skid trail and control plots) had a statistically significant effect on sediments. Regardless of the gradient classes and foliage periods, mean sediment in the skid trail (2.28 g) was 11.7 times significantly higher than in the control plots (0.18 g). However, there were no significant differences in the sediment production for either the control plots or the skid trail plots between the two slope classes. The sediment production was significantly highest in leaf-off period on the skid trail (4.26 g) followed by leaf-on period on the skid trail ≈ leaf-off period on the control ≈ leaf-on period on the control (Figure 4).

Regression analysis revealed that there was a significant linear relationship between the sediment and the rainfall for the skid trail and control plots in the two trail gradient (0-20% and 20-40%) for both the leaf-off and the leaf-on periods (Figure 5). A regression analysis between the runoff and the sediment revealed that the sediment significantly correlated with the runoff for the skid trail and the control plots for the two trail gradient and both the leaf-off and the leaf-on period (Figure 6).

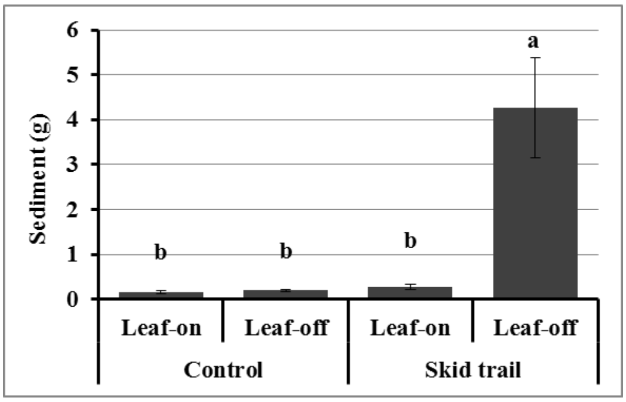

Figure 4. Mean sediment production in the skid trail and the control plot during leaf-on and leaf-off period

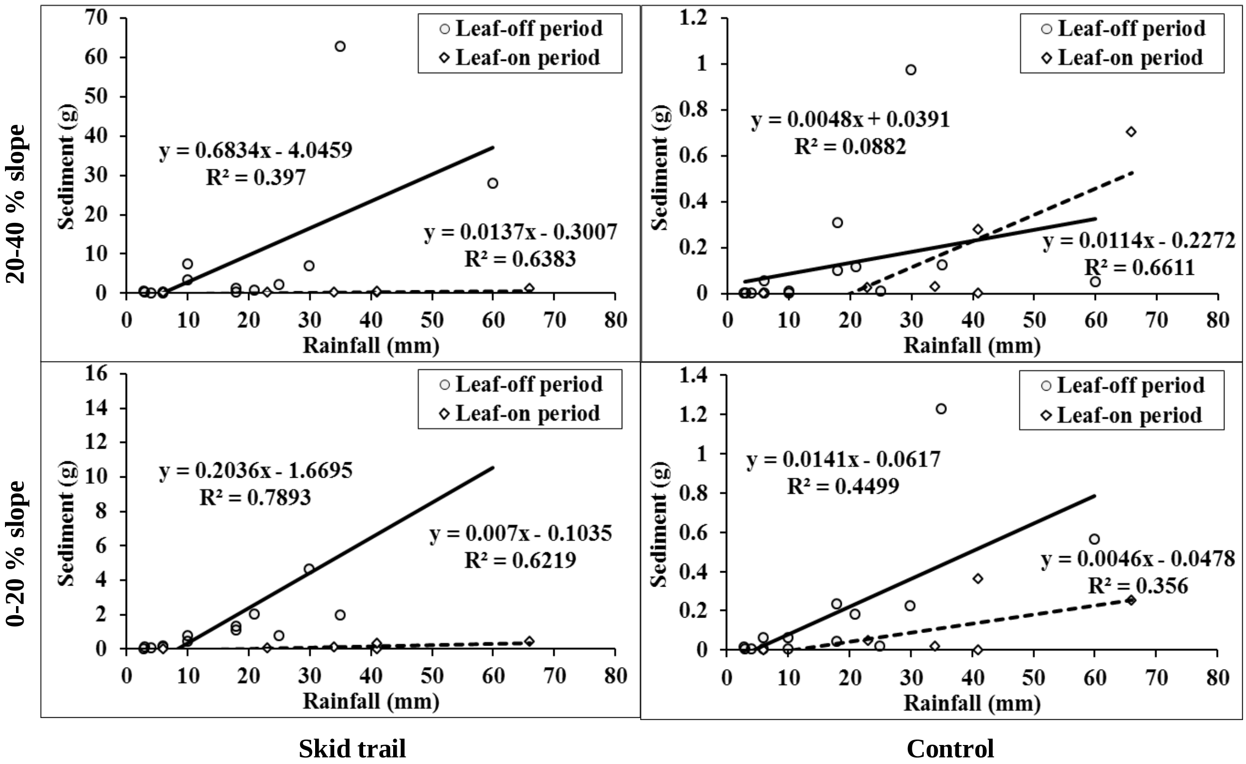

Figure 5. The relationship between sediment and rainfall for each slope gradient class (0–20% and 20–40%) for the skid trail and undisturbed area (control plots) in the treatments including leaf-off period and leaf-on period

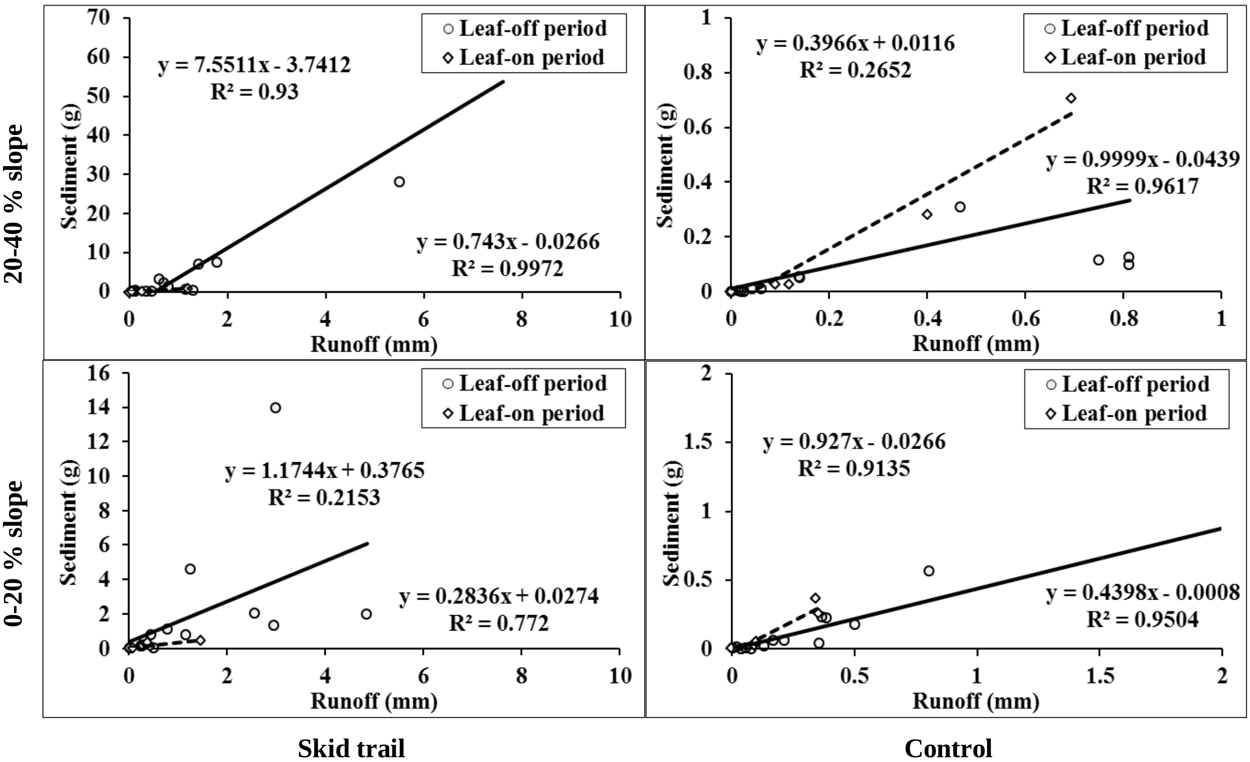

Figure 6. The relationship between runoff and sediment for each slope gradient class (0–20% and 20–40%) for the skid trail and undisturbed area (control plots) in the treatments including leaf-off period and leaf-on period

4. Discussion

The plot-scale measuring is best suited measuring method to characterize the hydrological processes and soil compaction at field experiments (Hartanto et al., 2003; Jourgholami et al., 2018a, b); hence, the on-site measuring methods was used to study the effects of logging operations on runoff and soil loss. The ground-based timber logging severely influenced the runoff and the sediment values in this study, thereby the results supported the hypotheses that removing litter layer, reducing organic matter, and enhancing soil bulk density would cause an increase in runoff and sediment production. The results showed that soil bulk density increased in the skid trails as the machine traffic intensities increased at the depth of the upper 4 cm of the soil profile. The significant effect of traffic intensity on soil bulk density in the two slope gradient categories was consistent with the findings of previous studies, which demonstrated substantial increase in soil bulk density and decrease of macro-pores with increase in the forest machinery traffic (Grace et al., 2006; Stuart and Edwards, 2006; Jourgholami et al., 2017a). The results of this research were consistent with those of several studies, which indicated that reduction of vegetation cover due to logging operations led to enhance the overland flow and the sediment production (Webb et al., 2012; Ide et al., 2013; Holz et al., 2015; Jourgholami et al., 2018a, b). In non-compacted forest soil such as in the control area of this study, the leaf litter layer can shield the mineral soil from raindrops.

Result of the regression analyses revealed that rainfall intensity was important parameters that explained the variation of the runoff and sediment. In the line with this study, previous studies revealed that the extent of soil loss was associated to rainfall intensity (Defersha and Melesse, 2012; El Kateb et al., 2013; Fang et al., 2015; Liu et al., 2015). The differences in results between the skid trails and the control plots can be attributed to the several factors. Firstly, spatial patterns of canopy for interception differed between during leaf-on and leaf-off periods. Secondly, a reduction in water infiltration capacity due to soil compaction exposed to the forestry machine traffic can be associated to an increase in runoff (Moore and Wondzell, 2005; Dung et al., 2012).

In this study, the slope gradients (two classes: 0–20% and 20–40%) did not statistically have significant effect on runoff and sediments. Since, in this study, the slope length was considered as 2 m plot long, hence, rill cannot be formed which was the major source of sediment since the distance was too short. In other hand, this plot-scale study measured only the rainsplash and sheetwash instead of the rill erosion (Sosa-Pérez and MacDonald, 2017a). In the line with the present study, several studies have shown that the slope gradient influences on runoff and soil erosion and the slope gradient, length, and shape are the most important parameters (Wischmeier and Smith, 1978; Fu et al., 2011; Sensoy and Kara, 2014). Moreover, Sensoy and Kara (2014) found a significant decrease with increasing the slope length. In addition, by increasing the trail gradient, the velocity of overland flow increases, the infiltration of runoff into soil decreases, which results in runoff and sediment increases (Ekwue and Harrilal, 2010; Fu et al., 2011; Fang et al., 2015).

In Hyrcanian deciduous forest, deciduousness during autumn (leaf-off period), which coincided with the greatest precipitation, resulted in increasing the surface waterflow. Additionally, the phenomenon of greening the tree branching and leaves (leaf-on period) resulted in decreased runoff in summer imposed by the evapotranspiration. In addition, the temperature of the warmest month ranges from 28°C to 35°C (Talebi et al., 2014). Hence, at the rain dominated sites such as Gorazbon district, the interception loss is greater in the leaf-on period than in the leaf-off period. Cover canopy interception leads to decrease throughfall reaching to surface litter later (Moore and Wondzell, 2005), which could be explained the runoff and sediment difference between leaf-on and leaf-off period on the both skid trail and the control plots in this study. To decrease the negative effects of forestry machine traffic on forest soil that could be useful in the Hyrcanian forest, many studies have advised some amendatory solutions to mitigate the runoff and sediment such as: the addition of slash to skid trails to increase ground cover (Wagenbrenner et al., 2015; Jourgholami et al., 2018a, b), the use of fiber mats (Grushecky et al. 2009), the rapid application of mulch (Prats et al., 2016a, b; Jourgholami and Etehadi Abari, 2017a), forestry best management practices as installing water-bars (Wade, 2010; Cristan et al., 2016; Jourgholami et al., 2019a, b).

5. Conclusions

According to the findings of this study, it can be concluded that logging operations should be limited to the designated trails, because machine traffic away from the skid trail can have a significant effect in increasing soil compaction, which results in overland flow, soil detachment, and sedimentation. Since skidding time occurred in the dry months in leaf-on period in northern Iran, the study area was prone to heavy rainfall in the leaf-off period from late September to November. These rainfalls lead to serious runoff flow and sediment deposition to downstream networks. In addition, the fall season (leaf-off period) that starts in late November in the deciduous forests, which results in the loss of canopy cover and its related interceptions. Due to the removal of litter layer in the skid trails after logging operations, water cannot be infiltrated into the soil, and thus results in surface runoff and overland flow. So, water diversion structures in the skid trails after skidding operations are recommended. Also, some of the best management practices to runoff and erosion on the skid trail are recommended to reduce the runoff and sediment.

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