https://doi.org/10.5552/crojfe.2022.1294

Evaluating the Effectiveness of Mulching for Reducing Soil Erosion in Skid Trail Switchbacks

Ahmad Solgi, Eric K. Zenner, Ramin Naghdi, Ali Masumian, Ramin Shoja, Farshad Keivan Behjou

Abstract

Forest operations can lead to increased runoff and soil loss on roads and skid trails. The aim of this study was to evaluate the effectiveness of two erosion control treatments applied to different segments of skid trails following six natural rainfall events. A total of 162 plots 10 m long by 4 m wide were established in a Hyrcanian deciduous forest to assess soil runoff and soil loss following ground-based harvesting traffic. The experimental setup consisted of three levels of traffic intensity (three, eight and 16 skidder passes), two levels of slope gradient (≤20% and >20%), three classes of curvature (narrow = high deflection angle, 60°–70°; wide = low deflection angle, 110°–130°, and straight trail segments), and three classes of mulch cover (bare soil, sawdust cover, and rice straw cover). Each treatment combination was replicated three times, yielding 972 soil samples. The average surface runoff volume and soil loss differed significantly between the switchbacks and the straight trail segments and depended strongly on the degree of curvature, with severity of adverse effects increasing with curve tightness. Mulch cover treatments had a significant ameliorating effect on the surface runoff volume and soil loss throughout the skid trail. The average runoff and soil loss from the skid trails treated with sawdust cover (SC) (0.24 l m^{-2} (mm) and 0.49 g m^{-2}, respectively) were lower than on trails covered with rice straw (RSC) (0.45 l m^{-2} and 1.19 g m^{-2}, respectively), which were, in turn lower than on untreated bare soil (BS) trail segments (0.70 l m^{-2} and 2.31 g m^{-2}, respectively). Surface runoff volume was significantly positively correlated with soil loss and both were positively correlated with dry bulk density and rut depth and negatively correlated with litter mass, total porosity, and macroporosity. Surface cover is a successful measure for controlling erosion losses following skidding disturbances, particularly in the switchback curves of trails on steep slopes where erosion potential is high.

Keywords: curve angle, rice straw, sawdust, soil compaction, soil loss

1. Introduction

Forest soil degradation is one of the major problems in ground-based skidding in mountainous forests. Traffic with heavy machinery is the main cause of top- and sub-soil compaction that can change the physical and chemical properties of the soil, soil fauna, and plant diversity (Naghdi et al. 2016a, Nawaz et al. 2013, Jourgholami et al. 2021b) and result in extensive damage that can persist for many years (McColl 1995, Sohrabi et al. 2020). Soil compaction refers to the compression of pores, which leads to decreased porosity and pore continuity, increased bulk density and soil strength, decreased gas exchange rates between soil and atmosphere, and lower water infiltration, which in turn leads to increased runoff (Solgi et al. 2014, Solgi et al. 2019a, Picchio et al. 2020).

Compaction in skid trails is considered the most important factor that affects the intensity and frequency of overland flow and surface wash erosion (Garcia-Ruiz 2010). Generally, both runoff and sediment loss increase exponentially with increasing compaction (Motavalli et al. 2003, Arnaez et al. 2004, Solgi et al. 2014). More specifically, the extent and severity of surface erosion on a skid trail is related to the slope gradient of the terrain (Akbarimehr and Naghdi 2012, Solgi et al. 2014, Jourgholami et al. 2021a), the traffic frequency of forest machines (Najafi et al. 2009, Solgi et al. 2014, Cambi et al. 2015), the applied loads (Battiato et al. 2013), the seasonality and rainfall intensity (Martínez-Zavala et al. 2008, Kinnell 2016), the soil texture, moisture content, and organic matter content (Areas et al. 2005, Croke et al. 2001, Masumian et al. 2017), the cover of ground vegetation (Cerdà 2007, Lee et al. 2013, Zemke 2016, Solgi et al. 2019a), and the time since construction of the skid trail (Fu et al. 2010). While thus affected by a number of factors, the erosional behavior of soils is particularly strongly influenced by the gradient of the terrain and the cover of the ground vegetation (Morgan 1986). In Hyrcanian forests of northern Iran, greatest amounts of runoff and sedimentation were observed in skid trails, followed by areas without canopy cover, selectively harvested areas, and unharvested control areas (Abari et al. 2017). As good ground surface cover of trees and understory can protect the soil surface from damaging storm energy, undisturbed forest areas generally suffer minimal erosion and sedimentation (Grace 2002). Ground cover also explained why even powerful storm events did not generate runoff and sediment on undisturbed control plots in a harvest area (Solgi et al. 2014).

To limit harvest disturbances of the soil, numerous soil erosion control techniques have been developed and encoded into best management practices (BMPs) in many countries. These practices are designed to achieve two significant objectives: to reduce the severity and extent of soil erosion at the harvest site to meet the allowable soil erosion criteria and to minimize the delivery of sediment and pollutants to natural drainage lines (Wallbrink and Croke 2002, Cristan et al. 2016). The installation of water diversion structures such as water bars is a very effective runoff and sediment control strategy that can limit sediment delivery to adjacent areas (Wallbrink and Croke 2002). Water bars can be applied where soil conditions, slope gradients or long slope lengths prevent other BMPs from providing effective control of soil erosion and sediment discharge. To adapt control measures to varying rainfall amounts and minimize the amount of sediment deposited into nearby streams, increasing water-bar frequency and surface roughness on skid trails through the addition of litter, logging debris brush or woody debris obtained during the processing phase have been recommended (Litschert and MacDonald 2009). Increased surface roughness dissipates the energy associated with the impact of raindrops, which may otherwise dislodge soil particles (Wischmeier and Smith 1958). Broadleaf and needle litter can also delay the beginning and reduce the amount of runoff, thus significantly reducing soil loss (Li et al. 2014). Further, contour-felled logs at distances of 20 and 30 m may mitigate even more effectively the runoff and sediment yields on machine operating trails than soil protective mats of leaf litter or straw mulch (Jourgholami et al. 2020).

While several studies have recently investigated the mitigation potential of different properties and types of soil protective mats on the extent and severity of soil erosion on skid trails (Akbarimehr and Naghdi 2012, Solgi et al. 2014, Sadeghi et al. 2016, Masumian et al. 2017, Lotfalian et al. 2019, Solgi et al. 2019a), a comparison of the effectiveness of soil protective mats of varying composition, particularly along the entire skid trail consisting of straight segments and switchback curves has received little attention thus far (Jourgholami and Abari 2017, Jourgholami et al. 2020). This is of particular interest because the effects of ground skidding on soil compaction may be much more serious in switchback curves than on straight trail segments and more so in narrow than wide curves (Solgi et al. 2019b).

This study used the frequency of ground-based skidder traffic and two gradients classes of the slope of the skid trail as design variables to contrast skidding effects on soil physical properties and surface runoff and soil loss in a mountainous Hyrcanian forest. Two main research questions were addressed:

⇒ do adverse effects of skidding on soil physical properties that generally increase with increased skidder traffic and slope gradient also differ between straight trail sections and switchback curves and, if so, further depend on the degree of curvature of the switchback curves

⇒ do ameliorative effects of two different types of soil protective mats applied on skid trails following skidding differentially reduce amounts of surface runoff and soil loss relative to bare soil and, if so, does the ameliorative effect differ between straight trail sections and switchback curves and further depend on the degree of curvature of the switchback curves?

2. Material and Methods

2.1 Site Description

The research was conducted in the Shenrood forest, Guilan province, northern Iran between (36°13-15' N and 53°10-15' E) between January and March 2019. The forest is composed of deciduous trees dominated by oriental beech (*Fagus orientalis* Lipsky) and common hornbeam (*Carpinus betulus* (L.)) along with caucasian alder (*Alnus subcordata* (C.A.M)) and chestnut-leaved oak (*Quercus castaneifolia* (C.A. Mey)) as companion species. The soil class is a Cambisol (World Reference Base (WRB), FAO 2015). Soil texture along the skid trail to a depth of 10 cm was a clay loam with a particle size distribution of 38% clay (<0.002 mm size), 29% silt (0.002–0.05 mm), and 33% sand (0.05–2 mm) (based on the Bouyoucos hydrometer method). The elevation of the study site ranged between approximately 800–950 m above sea level with a northern aspect. The average annual rainfall recorded at the closest national weather station located 20 km from the research area is 1130 mm with a maximum mean monthly rainfall of 140 mm in October and a minimum rainfall of 25 mm in August. The mean annual temperature is 16 °C, with lowest temperatures in February. At the time of skidding, weather conditions were dry and warm with an average gravimetric soil moisture content of 20%. The soil had not been driven on before the experiment.

Fig. 1 Rubber tired skidder (Timberjack 450 C) used in this study

2.2 Forest Operations and Machine Specifications

At the study site, a combination of group selection and single-tree selection silvicultural harvests were applied. In Hyrcanian forests, harvesting and silviculture operations are most common in the autumn and winter, while extraction of logs is usually completed in the spring and summer. Harvesting operations were done by hand felling and processing, followed by transportation of the logs from the forest stand to the roadside by a rubber-tired Timberjack 450C cable skidder (no chains or tracks were installed on the skidder during skidding) (Fig. 1; Table 1).

Felling by chainsaws is the most common harvesting technique in Iran. The rubber-tired cable skidder is typically used to extract 3 to 4 m long logs on drivable terrain of up to a gradient of 30 percent. In the experiments, the skidder was driven unloaded to avoid distorting results with different timber weights in repeated equipment passes.

Table 1 Main technical characteristics of Timberjack 450C skidder

Specifications	Timberjack 450C
Weight, kg	10,257
Number of wheels	4
Tire size, mm	775×813
Ground pressure, kPa	221
Engine power, hp	177
Year of manufacture	1998
Manufacturing location	Canada

2.3 Experimental Design and Data Collection

For this study, a skid trail of 2300 m length was delineated prior to harvesting. The skid trail encompassed a range of longitudinal slope steepness with no lateral slope and required establishment of multiple switchback curves with varying curvature. In the skid trail, three types of curvature were established: narrow curves with a deflection angle of 60°–75°, wide curves with a deflection angle of 110°–130° and straight sections of the skid trail without deflection angle (straight trail). As previous studies have repeatedly demonstrated increased soil damage on slopes with gradients >20% (e.g., Solgi et al. 2018, 2019a, 2019b), sampling skidding effects along the longitudinal profile considered two slope classes (≤20% and >20%). The slope class ≤20% included trail sections that ranged from 6–14% in gradient, whereas the slope class >20% contained sections with a range of 25–30%. Traffic frequencies of the unloaded skidder were:

⇒ three passes (light traffic)
⇒ eight passes (moderate traffic)
⇒ 16 passes (heavy traffic).

Each treatment plot was 10 m long by 4 m wide, with a buffer of at least 2 m between plots to avoid interactions. In each plot, four ecological variables, i.e., bulk density, total porosity, macroporosity, and mass of the forest floor as well as rutting depth were also measured. Five sample lines were delineated perpendicular to the trail with a 2 m buffer zone between lines

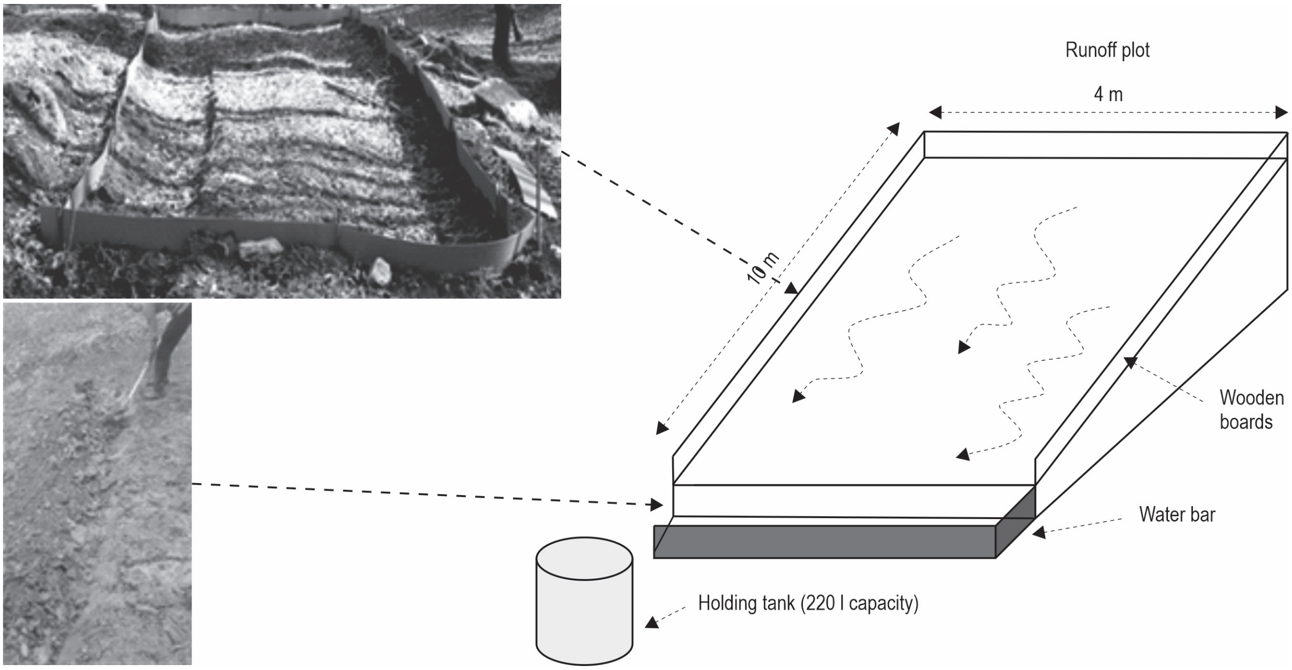

Fig. 2 Layout of sample areas

and three lines were randomly selected for measurements of soil physical properties. Soil samples were collected in the left wheel track (LWT) and right wheel track (RWT) of the skidder and averaged. Therefore, six soil samples were collected from of the 162 treatment plot, totaling 972 soil samples.

Soil samples weighing on average 341 g were collected with a soil hammer and rings (diameter 5 cm, length 10 cm) and immediately put in polyethylene bags and labeled. Collected samples, brought to the laboratory from the research area, were promptly weighed (soil samples). Soil and forest floor samples were dried in an oven at 105°C (24 h) and 65°C (48 h), respectively. The water content in the soil samples was measured gravimetrically after drying in an oven (Kalra and Maynard 1991).

Dry soil bulk density (D_b, g cm^{-3}) was calculated as Eq. (1):

$$D_b = D_b/VC \quad (1)$$

Where:

W_d weight of dry soil (g)

VC volume of soil cores (196.25 cm^3).

Total soil porosity (TP, %) was calculated as Eq. (2):

$$TP = (1 - D_b/2.65) \times 100 \quad (2)$$

Where:

2.65 g cm^{-3} is soil particle density (Freeze and Cherry 1979).

Macroporosity (MP, %) was determined using the water description method (Danielson and Sutherland 1986). In this method, soil samples were saturated in plastic tubes over a period of 5 days; the water level was slowly raised to prevent air entrapment and weighed. The samples were then drained for 3 h and weighed again (Rivenshield and Bassuk 2007, Solgi et al. 2019c). We calculated the macroporosity based on Eq. (3):

$$MP = [(W_s - W_{dr})/V] \times 100 \quad (3)$$

Where:

W_s represents saturated weight, g

W_{dr} specifies drained weight, g

V refers to volume, cm^3.

Ruts of at least 5 cm depth from the top of the mineral soil surface and 2 m long were also sampled. Rut depth was measured using a profile meter consisting of a set of vertical metal rods (length 500 mm and diameter 5 mm), spaced at 25 mm horizontal intervals, sliding through holes in a 1 m long iron bar. The bar was placed across the wheel tracks perpendicular to the direction of travel and rods positioned to conform to the shape of the depression (Nugent et al. 2003). Rut depth was calculated as the average depth of 40 reads on the 3,28 ft bar (see Fig. 3). Forest floor samples were taken by collecting the entire forest floor of 1 m^2 soil surface.

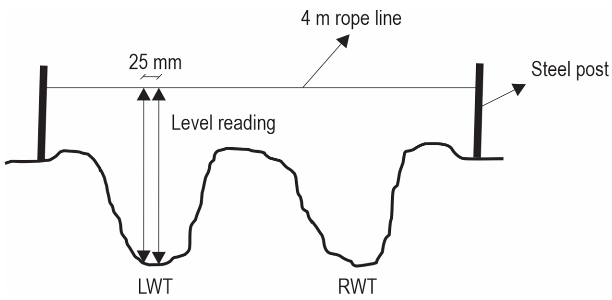

Fig. 3 Illustration of technique used for measuring rut depth

Following skidding and sampling of soil physical characteristics and forest floor, the skid trail was covered with different protective mats to prevent soil erosion. To measure subsequent soil erosion, treatment plots were surrounded by wooden boards that were 30 cm in height and inserted 10 cm deep into the soil to control surface water movement from the inside to the outside of the plot area and vice-versa (Solgi et al. 2014). A water bar was constructed on the lower side of each treatment plot so that all surface water runoff from inside the area could be collected in a holding tank with the capacity of 220 liters (Fig. 2). The inclination of a water bar is important for slowing and diverting water from the skid trail and, since a slope of 2–4% is ideal, water bars were installed with a 3% out-slope at a depth of 30–35 cm. A collecting trough made of a metal sheet and covered with a plastic or sheet metal to prevent direct entry of rainfall was positioned at the downslope end of the plot. The volume of surface runoff was computed by measuring the height of the water in the collecting tanks. To determine the sediment concentration of each plot, all the sediments from the collected runoff sample were thoroughly mixed and brought into suspension before taking a 1-liter sample for analysis. The samples were then taken to the laboratory where the sediment was filtered, oven-dried at 105°C for a day and weighed (drying and weighing method) (Sadeghi et al. 2007).

Over the study period, six rainfall/sampling events occurred. As the measuring equipment was stolen from the site, we were unable to measure rainfall amounts of each event at the site, which ranged between 4.5 and 54.5 mm at the nearest climate station 20 km from the site. Immediately after each rainfall event ended, tanks were emptied and cleaned. Average values of the response variables of surface runoff and soil loss across the six rainfall/sampling events were related to bare soil (BS, control) and two types of soil protective covers: sawdust mulch cover (SC) and rice straw cover (RSC). Protective sawdust mats were produced from oriental beech (50%) and common hornbeam (50%) trees and obtained from a sawmill near the study site. The rice straw mat was on average 3–15 cm long and 0.3–0.5 mm thick. Sawdust (5.2 kg m^{-2}) and rice straw (2.4 kg m^{-2}) were applied at a rate that initially gave 100% coverage (thickness of 1 cm) (Fernández and Vega 2016). A total of 162 runoff plots were installed that included 54 combinations of two levels of trail gradient (G), three levels of traffic frequency (T), three levels of curvature (C), and three levels of mulch cover (M), each replicated three times (2G×3T×3C×3M×3 replicates).

2.4 Statistical Analysis

The experimental design was a factorial arrangement of treatments conducted in a completely randomized design. Following the application of Kolmogorov–Smirnov tests to check normality and Levene tests to check homogeneity of variance, three-way (soil physical characteristics) and four-way (runoff and soil loss) ANOVAs were used to assess the significance of observed differences in average D_b, *TP*, *MP*, mass of the forest floor, rut depth, runoff and soil loss under different conditions of traffic levels, trail slopes, curvature, and mulch cover types and to assess the significance of interactions of the main effects. Tukey's *HSD* test was used to determine the significance of differences between average D_b, *TP*, *MP*, mass of the forest floor, rut depth, runoff and soil loss for different treatments (Zar 1999). The SPSS 11.5 statistical package was used for statistical analyses.

3. Results

In undisturbed (control) areas, dry bulk density (D_b, range: 0.69–0.71 g cm^{-3}), total porosity (*TP*, range: 73.7–75.1%), and macroporosity (*MP*, range: 44.8–45.6%) did not differ significantly between slope gradients (Table 2).

Following traffic, D_b increased to 0.89–1.56 g cm^{-3}, *TP* decreased to 68.9–37.8%, and *MP* decreased to 38.6–9.2%. All three variables were significantly affected by traffic intensity, slope gradient and curvature class (Table 3).

Regardless of the degree of curvature, D_b increased, and *TP* and *MP* decreased consistently with increasing traffic intensity on both slope gradients and with increasing slope gradient at all traffic intensities (Table 2). Average values of D_b, *TP*, and *MP* differed significantly between switchbacks and straight skid trail segments and depended strongly on the degree of curvature (Table 3). On average, D_b was greatest in narrow

Table 2 Means (±std) of soil properties in an undisturbed control area (UN) and following different passes of a Timberjack 450C skidder on a skid trail on two slope gradients (≤20% and >20%) and three curvature classes (high deflection angle of 60–70° = narrow curves; low deflection angle of 110–130° = wide curves; and straight trail)

Curvature classes	Trail slope							
	≤20%				>20%			
	UN	3	8	16	UN	3	8	16
Dry bulk density, g cm^{-3}								
Straight	0.69^{Ad}±0.08	0.89^{Bc}±0.07	1.12^{Bb}±0.09	1.31^{Ba}±0.13	0.71^{Ad}±0.07	1.03^{Bc}±0.09	1.25^{Bb}±0.13	1.41^{Ba}±0.16
Wide curve	0.69^{Ad}±0.08	0.92^{Bc}±0.08	1.20^{Bb}±0.13	1.37^{ABa}±0.15	0.71^{Ad}±0.07	1.09^{ABc}±0.09	1.30^{Bb}±0.11	1.48^{ABa}±0.14
Narrow curve	0.69^{Ad}±0.08	1.01^{Ac}±0.11	1.32^{Ab}±0.14	1.46^{Aa}±0.11	0.71^{Ac}±0.07	1.14^{Ab}±0.12	1.51^{Aa}±0.17	1.56^{Aa}±0.19
Total porosity, %								
Straight	73.7^{Aa}±5.14	68.93^{Ab}±4.56	53.52^{Ac}±3.16	45.82^{Ad}±2.85	75.1^{Aa}±4.96	61.73^{Ab}±3.57	48.11^{Ac}±3.07	42.66^{Ad}±2.62
Wide curve	73.7^{Aa}±5.14	67.82^{Ab}±4.71	50.59^{Ac}±2.81	44.70^{Ad}±3.02	75.1^{Aa}±4.96	59.38^{Ab}±3.29	45.69^{Ac}±2.81	40.26^{ABd}±2.44
Narrow curve	73.7^{Aa}±5.14	62.04^{Bb}±3.82	45.73^{Bc}±2.65	42.11^{Ad}±2.95	75.1^{Aa}±4.96	53.07^{Bb}±3.31	38.60^{Bc}±2.33	37.82^{Bc}±2.18
Macroporosity, %								
Straight	44.8^{Aa}±3.06	38.57^{Ab}±2.76	20.53^{Ac}±1.81	14.07^{Ad}±1.44	45.6^{Aa}±3.25	29.13^{Ab}±2.48	15.18^{Ac}±1.49	12.21^{Ad}±1.26
Wide curve	44.8^{Aa}±3.06	38.24^{Ab}±2.64	16.31^{Bc}±1.56	13.28^{Ad}±1.29	45.6^{Aa}±3.25	28.33^{Ab}±2.39	14.01^{Ac}±1.57	10.69^{ABd}±1.15
Narrow curve	44.8^{Aa}±3.06	29.56^{Bb}±2.35	13.88^{Cc}±1.33	12.07^{Ad}±1.41	45.6^{Aa}±3.25	20.36^{Bb}±1.77	9.77^{Bc}±1.03	9.24^{Bc}±0.91
Forest floor, kg ha^{-1}								
Straight	3489.6^{Aa}±248	2859.4^{Ab}±203	1365.3^{Ac}±115	825.6^{Ad}±86	3463.5^{Aa}±227	2384.1^{Ab}±187	985.7^{Ac}±67	466.9^{Ad}±32
Wide curve	3489.6^{Aa}±248	2674.3^{Ab}±198	1183.7^{Bc}±85	503.2^{Bd}±49	3463.5^{Aa}±227	2247.3^{Ab}±163	739.6^{Ac}±43	155.3^{Bd}±15
Narrow curve	3489.6^{Aa}±248	2007.4^{Bb}±174	545.8^{Cc}±61	136.2^{Cd}±21	3463.5^{Aa}±227	1245.1^{Bb}±104	86.5^{Bc}±12	0^{Cd}±
Rut depth, cm								
Straight	0^{Ab}	0^{Bb}	0^{Cb}	5.3^{Ca}±0.31	0^{Ac}	0^{Cc}	3.4^{Cb}±0.18	9.1^{Ca}±0.69
Wide curve	0^{Ac}	0^{Bc}	2.7^{Bb}±0.11	7.5^{Ba}±0.52	0^{Ad}	1.6^{Bc}±0.09	5.8^{Bb}±0.35	13.9^{Ba}±0.94
Narrow curve	0^{Ad}	4.6^{Ac}±0.24	10.2^{Ab}±0.84	17.5^{Aa}±1.08	0^{Ad}	7.7^{Ac}±0.43	23.5^{Ab}±1.38	35.4^{Aa}±2.07

Values are mean and different letters within each treatment shows significant differences ($P<0.05$)
Capital case letters refer to the comparison made among three curvature classes for each skidding cycle and slope class separately (column)
Lower case letters refer to the comparison made among three skidding cycles at each slope category for various curvature classes (row)

Table 3 Analysis of variance (*P*-values) of effects of number of passes, trail slope and curvature class on soil physical properties

Source of variable	d.f.	*P*-values				
		Bulk density	Total porosity	Macro porosity	Forest floor	Rut depth
Passes	2	**≤0.05**	**≤0.05**	**≤0.05**	**≤0.05**	**≤0.05**
Slope	1	**≤0.05**	**≤0.05**	**≤0.05**	**≤0.05**	**≤0.05**
Curvature class	2	**≤0.05**	**≤0.05**	**≤0.05**	**≤0.05**	**≤0.05**
Passes × Slope	2	**≤0.05**	0.732	0.429	**≤0.05**	0.315
Passes × Curvature	4	**≤0.05**	0.164	0.128	**≤0.05**	**≤0.05**
Slope × Curvature	2	0.358	**≤0.05**	**≤0.05**	0.427	0.573
Passes × Slope × Curvature	4	**≤0.05**	0.262	**≤0.05**	0.646	**≤0.05**

P-values less than 0.05 are given in bold curves on steep terrain (1.41 g cm^{-3}) and least in straight segments on gentle terrain (1.10 g cm^{-3}). Compared to undisturbed (control) areas, traffic increased the average D_b by 27–101% on straight trail segments, 31–111% in wide curves, and 44–123% in narrow curves (Table 4). Traffic decreased the average *TP* by 7–42% on straight trail segments, 9–46% in wide curves, and 17–49% in narrow curves and decreased the average *MP* by 14–73% on straight trail segments, 15–76% in wide curves, and 35–80% in narrow curves (Table 4).

Forest floor removal in the skid trail occurred during the process of log removal and was highly variable in spatial extent and severity. Forest floor removal on the skid trail ranged from an 18% decline in biomass (3 passes and slope of ≤20% in straight trail segments) to complete removal of biomass (16 passes and slope of >20% in narrow curves) such that both remaining masses of forest floor material (Table 2) were significantly smaller than those of undisturbed area (3489.6 kg ha^{-1}). Removal of forest floor biomass occurred more rapidly on the steeper skid trail at each traffic frequency. For example, in narrow curves the amount of forest floor biomass lost after three passes on a gradient >20% was almost equal to that of eight passes on a gradient ≤20%. The average biomass values of the remaining forest floor material differed significantly between switchbacks and straight trail segments and depended strongly on the degree of curvature (Table 2). Compared to undisturbed (control) areas, traffic decreased the average forest floor biomass by 18–87% on straight trail segments, 23–95% in wide curves, and 42–100% in narrow curves (Table 4).

Rut depth was significantly affected by traffic intensity, slope gradient, curvature class, as well as the interactions of slope gradient × curvature class and the interactions of traffic intensity × slope gradient × curvature class (Table 3). The interactions clearly show that the increase of rut depth with increasing traffic intensity depended on the slope gradient as well as the degree of curvature. No rutting was observed in straight trail segments and wide curves after light traffic on slope gradients ≤20%. In contrast, rutting was already observed after light traffic in narrow curves on slope gradients >20% and ruts were nearly twice as deep on the steeper compared to the gentler slope gradient.

Following skidding operations, the average surface runoff volume (range: 0.14–1.58 l mm^{-2}), was significantly affected by the main effects, the interactions of slope gradient × curvature class, slope gradient × mulch cover, the three-way interaction of slope gradient × curvature class × mulch cover, and the four-way interaction of traffic intensity × slope gradient × curvature class × mulch cover. Similarly, the average soil loss (range: 0.26–7.06 g m^{-2}), was significantly affected by the main effects, the interactions of traffic intensity × mulch, traffic intensity × curvature class, slope gradient × mulch, and the three-way interactions of traffic intensity × slope gradient × mulch cover, and slope gradient × curvature class × mulch cover (Table 5).

Table 4 Mean relative change in soil property parameters (%). Relative change was determined as changes between trafficked and undisturbed (control) plots

Curvature classes	Trail slope					
	≤ 20%			> 20%		
	3	8	16	3	8	16
Dry bulk density, g cm^{-3}						
Straight	27.1	60.0	87.1	47.1	78.6	101.4
Wide curve	31.4	71.4	95.7	55.7	85.7	111.4
Narrow curve	44.3	88.6	108.6	62.8	115.7	122.8
Total porosity, %						
Straight	–7.3	–28.1	–38.4	–17.0	–35.3	–42.7
Wide curve	–8.8	–32.0	–39.9	–20.2	–38.6	–45.9
Narrow curve	–16.6	–38.5	–43.4	–28.7	–48.1	–49.2
Macroporosity, %						
Straight	–14.7	–54.6	–68.9	–35.5	–66.4	–73.0
Wide curve	–15.4	–63.9	–70.6	–37.3	–69.0	–76.30
Narrow curve	–34.6	–69.3	–73.3	–54.9	–78.4	–79.5
Forest floor, kg h^{-1}						
Straight	–18.1	–60.9	–76.3	–31.7	–71.7	–86.6
Wide curve	–23.3	–66.1	–85.6	–35.6	–78.8	–95.5
Narrow curve	–42.5	–84.3	–96.1	–64.3	–97.5	–100

The average surface runoff volume and soil loss under natural rainfall increased consistently with increasing traffic intensity on both slope gradients and with increasing slope gradient at all traffic intensities and depended strongly on the degree of curvature and differed significantly between switchbacks and straight skid trail segments (Tables 6 and 7).

Mulch cover treatments significantly reduced the surface runoff volume and soil loss compared to bare forest soil (Table 6 and 7). The average runoff and soil loss from the skid trails were lower when covered with sawdust cover (SC) (0.244 l mm^{-2}, 0.49 g m^{-2}) than rice straw cover (RSC) (0.453 l mm^{-2}, 1.19 g m^{-2}), which was

Table 5 Analysis of variance (*P*-values) of effects of number of passes, trail slope and curvature class on surface runoff and soil loss

Source of variable	d.f.	*P*-values	
		Runoff	Soil loss
Passes	2	**≤0.05**	**≤0.05**
Slope	1	**≤0.05**	**≤0.05**
Curvature	2	**≤0.05**	**≤0.05**
Mulch	2	**≤0.05**	**≤0.05**
Passes × Slope	2	0.624	0.251
Passes × Curvature	4	0.181	**≤0.05**
Passes × Mulch	2	0.552	**≤0.05**
Slope × Curvature	2	**≤0.05**	0.163
Slope × Mulch	2	**≤0.05**	**≤0.05**
Passes × Slope × Curvature	4	0.248	0.144
Passes × Slope × Mulch	4	0.339	**≤0.05**
Slope × Curvature × Mulch	4	**≤0.05**	**≤0.05**
Passes × Curvature × Mulch	8	0.219	0.408
Passes × Slope × Curvature × Mulch	8	**≤0.05**	0.126

P-values less than 0.05 are given in bold

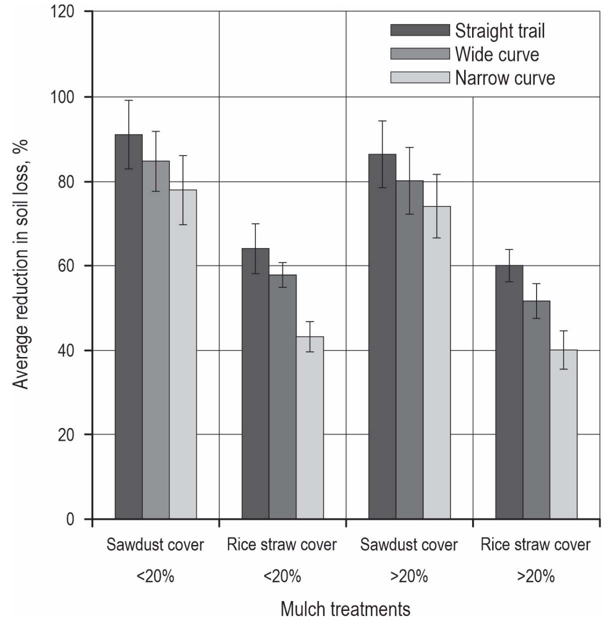

Fig. 4 Average reduction in soil loss (%) compared to control treatment (bare soil)

lower than bare soil (BS) trail segments (0.70 l mm^{-2}, 2.31 g m^{-2}). The SC and RSC treatment reduced runoff and soil erosion/loss by 79% and 48%, respectively, compared to the bare soil (control) treatment (Fig. 4).

The correlation analysis indicated that runoff and soil loss were significantly correlated with bulk density, total porosity, macroporosity, litter mass, and rut depth (Table 8). Surface runoff volume was significantly positively correlated with soil loss and both were positively correlated with dry bulk density and rut depth and negatively correlated with litter mass, total porosity and macroporosity.

4. Discussion

The observed progressive increase in soil bulk density and rutting and reduction in microporosity, total porosity, and forest floor biomass following increased traffic frequency of ground-based skidding machinery, which led to more soil surface runoff and erosion, particularly on the steeper slope gradient, was expected from previous research (e.g., Greacen and Sands 1980, Froehlich et al. 1981, Eliasson 2005, Botta et al. 2006, Najafi et al. 2009, Najafi et al. 2009, 2010, Naghdi et al. 2015, 2016b, Solgi and Najafi 2014, Solgi et al. 2015, 2018, 2019a). What was unexpected, however, was the magnitude of the adverse effect size of skidding in increasingly narrow curves that was consistently observed for D_b, *MP*, and *TP*. For example, values of D_b, *MP*, and *TP* after three passes through narrow switchback curves on gentle slopes corresponded to those after three passes on straight segments on steep slopes and values after eight passes on straight segments on gentle slopes corresponded to three passes through narrow curves on steep slopes. Thus, for the same traffic frequency, skidding through narrow curves on gentle slopes results in roughly the equivalent soil damage as skidding through wider curves on steep slopes; similarly, soil damage after skidding through wide curves on gentle slopes is comparable to that on narrow trail segments on steep slopes.

A likely explanation for stronger adverse effects of skidding on D_b, *MP*, *TP*, and rutting on steep slopes and more narrow switchback curves are the physical forces exerted on the soil that reflect the difficulties of skidding in steep terrain (Pacejka 2012). Machines typically slow their speed on steeper trails and when entering and passing through narrower switchback curve (Thawornwong 1996, Solgi et al. 2019b) and may slip continuously on steeper trails and in narrower curves, thus remaining in a given place for a longer period of time, which results in greater vibrations and

Table 6 Means (±std) of surface runoff volume (mm) following different numbers of passes of a Timberjack 450C skidder on a skid trail on two slope gradients (≤20% and >20%) and three curvature classes (high deflection angle of 60–70° = narrow curves; low deflection angle of 110–130° = wide curves; and straight trail)

Mulch treatments	Trail slope					
	≤20%			>20%		
	3	8	16	3	8	16
Straight trail segments						
Bare soil	$0.140^{Ac}\pm0.018$	$0.320^{Ab}\pm0.025$	$0.814^{Aa}\pm0.057$	$0.223^{Ac}\pm0.015$	$0.716^{Ab}\pm0.048$	$1.154^{Aa}\pm0.081$
Rice straw cover	$0.052^{Bc}\pm0.001$	$0.121^{Bb}\pm0.009$	$0.382^{Ba}\pm0.027$	$0.105^{Bc}\pm0.009$	$0.387^{Bb}\pm0.032$	$0.642^{Ba}\pm0.054$
Sawdust cover	$0.0133^{Cc}\pm0.001$	$0.038^{Cb}\pm0.002$	$0.106^{Ca}\pm0.007$	$0.036^{Cc}\pm0.003$	$0.147^{Cb}\pm0.012$	$0.229^{Ca}\pm0.018$
Wide curve segments						
Bare soil	$0.159^{Ac}\pm0.012$	$0.385^{Ab}\pm0.034$	$0.873^{Aa}\pm0.067$	$0.257^{Ac}\pm0.198$	$0.806^{Ab}\pm0.067$	$1.22^{Aa}\pm0.087$
Rice straw cover	$0.092^{Bc}\pm0.007$	$0.236^{Bb}\pm.018$	$0.568^{Ba}\pm0.047$	$0.17^{Bc}\pm0.014$	$0.523^{Bb}\pm0.04$	$0.856^{Ba}\pm0.071$
Sawdust cover	$0.042^{Cc}\pm0.003$	$0.112^{Cb}\pm0.008$	$0.271^{Ca}\pm0.025$	$0.088^{Cc}\pm0.006$	$0.293^{Cb}\pm0.024$	$0.477^{Ca}\pm0.037$
Narrow curve segments						
Bare soil	$0.263^{Ac}\pm0.022$	$0.670^{Ab}\pm0.052$	$1.237^{Aa}\pm0.112$	$0.436^{Ac}\pm0.029$	$1.311^{Ab}\pm0.094$	$1.580^{Aa}\pm0.104$
Rice straw cover	$0.182^{Bc}\pm0.014$	$0.464^{Bb}\pm0.036$	$0.891^{Ba}\pm0.064$	$0.318^{Bc}\pm0.023$	$0.973^{Bb}\pm0.065$	$1.185^{Ba}\pm0.085$
Sawdust cover	$0.104^{Cc}\pm0.008$	$0.283^{Cb}\pm0.020$	$0.542^{Ca}\pm0.042$	$0.198^{Cc}\pm0.014$	$0.618^{Cb}\pm0.044$	$0.796^{Ca}\pm0.061$

Values are mean and different letters within each treatment shows significant differences ($P<0.05$)
Capital case letters refer to the comparison made among three mulch treatments for each skidding cycle and slope class separately (column)
Lower case letters refer to the comparison made among three skidding cycle at each slope categories for the various mulch treatments (row)

Table 7 Means (±std) of soil loss (g m^{-2}) following different numbers of passes of a Timberjack 450C skidder on a skid trail on two slope gradients (≤20% and >20%) and three curvature classes (high deflection angle of 60–70° = narrow curves; low deflection angle of 110–130° = wide curves; and straight trail)

Mulch treatments	Trail slope					
	≤ 20%			> 20%		
	3	8	16	3	8	16
Straight trail segments						
Bare soil	$0.26^{Ac}\pm0.03$	$0.72^{Ab}\pm0.08$	$1.74^{Aa}\pm0.13$	$0.61^{Ac}\pm0.07$	$1.46^{Ab}\pm0.09$	$4.65^{Aa}\pm0.35$
Rice straw cover	$0.09^{Bc}\pm0.01$	$0.26^{Bb}\pm0.03$	$0.65^{Ba}\pm0.06$	$0.24^{Bc}\pm0.04$	$0.58^{Bb}\pm0.06$	$1.91^{Ba}\pm0.22$
Sawdust cover	$0.02^{Cc}\pm0.007$	$0.06^{Cb}\pm0.009$	$0.20^{Ca}\pm0.03$	$0.07^{Cc}\pm0.009$	$0.21^{Cb}\pm0.03$	$0.72^{Ca}\pm0.07$
Wide curve segments						
Bare soil	$0.33^{Ac}\pm0.04$	$0.80^{Ab}\pm0.06$	$1.95^{Aa}\pm0.15$	$0.69^{Ac}\pm0.06$	$1.87^{Ab}\pm0.18$	$5.21^{Aa}\pm0.42$
Rice straw cover	$0.13^{Bc}\pm0.03$	$0.34^{Bb}\pm0.05$	$0.88^{Ba}\pm0.09$	$0.33^{Bc}\pm0.04$	$0.92^{Bb}\pm0.08$	$2.52^{Ba}\pm0.27$
Sawdust cover	$0.05^{Cc}\pm0.009$	$0.12^{Cb}\pm0.02$	$0.32^{Ca}\pm0.04$	$0.13^{Cc}\pm0.02$	$0.37^{Cb}\pm0.05$	$1.12^{Ca}\pm0.07$
Narrow curve segments						
Bare soil	$1.24^{Ac}\pm0.11$	$2.35^{Ab}\pm0.17$	$3.83^{Aa}\pm0.35$	$2.17^{Ac}\pm0.21$	$4.59^{Ab}\pm0.41$	$7.06^{Aa}\pm0.64$
Rice straw cover	$0.69^{Bc}\pm0.05$	$1.34^{Bb}\pm0.12$	$2.22^{Ba}\pm0.23$	$1.28^{Bc}\pm0.10$	$2.75^{Bb}\pm0.28$	$4.31^{Ba}\pm0.32$
Sawdust cover	$0.26^{Cc}\pm0.02$	$0.52^{Cb}\pm0.03$	$0.91^{Ca}\pm0.07$	$0.54^{Cc}\pm0.04$	$1.17^{Cb}\pm0.08$	$1.96^{Ca}\pm0.20$

Values are mean and different letters within each treatment shows significant differences ($P<0.05$)
Capital case letters refer to the comparison made among three mulch treatments for each skidding cycle and slope class separately (column)
Lower case letters refer to the comparison made among three skidding cycle at each slope categories for the various mulch treatments (row)

Table 8 Spearman correlation coefficients between runoff, soil loss, and ecological factors

Code	Variables	1	2	3	4	5	6	7
1	Runoff	1.00	0.964**	0.836**	–0.759**	–0.887**	–0.935**	0.627*
2	Soil loss	–	1.00	0.925**	–0.784**	–0.804**	–0.879**	0.531*
3	Bulk density	–	–	1.00	–0.943**	–0.968**	–0.832**	0.544*
4	Total porosity	–	–	–	1.00	0.983**	0.825**	–0.614*
5	Macroporosity	–	–	–	–	1.00	0.795**	–0.558*
6	Forest floor biomass	–	–	–	–	–	1.00	–0.669*
7	Rut depth	–	–	–	–	–	–	1.00

**Significant at the 0.01 level
* Significant at the 0.05 level

compaction (Solgi et al. 2017) and more puddling and dragging of the topsoil (Gayoso and Iroumé 1991) compared to more gentle trails or narrow skid trail sections that are traversed with higher speeds (Horn et al. 1989, Solgi and Najafi 2014). In addition, machine weight distribution changes when driving uphill on steep trails or through narrow curves. Driving uphill on steep trails shifts a greater load/weight of the machine onto the rear axle than in flat terrain, increasing the probability that the wheels could slip, which pushes soil particles closer together and increases soil compaction (Frey et al. 2009) and rut depth (Botta et al. 2006, Najafi et al. 2009, Solgi et al. 2016). In more narrow curves, lateral weight/load transfer, which is the change in the distribution of the weight of the machine and its load and thus a higher pressure on the wheels on the outside of the curve (and lower ground pressure of the wheels on the inside of the curve) (Solgi et al. 2019b) results in an uneven soil degradation of the wheel tracks within the skid trail (Pacejka 2012). As the physical forces are particularly pronounced in narrow curves (Pacejka 2012), soils in skid trails with narrow curves are more susceptible to greater compaction and deeper ruts than in wide curves (Solgi et al. 2019c). Compaction and rut depth are a measure of severity of traffic or soil disturbance and the greater D_b and the deeper the rut, presumably the more severely the soil is disturbed (Heninger et al. 2002). It is worth pointing out that D_b values on straight trails and in curves reached 1.40-1.56 g cm^{-3}, which is close to critical values above which plant roots cannot penetrate soils with fine and medium texture (Kozlowski 1999), after 16 machine passes on steep slopes and already after eight passes in narrow curves on gentle slopes, indicating that narrow curves are at a greater risk to become impenetrable by the roots of tree regeneration after fewer passes. It should also be remembered that the skidder was driven unloaded and that the added weight of logs means that adverse effects and these critical values would likely have been reached with fewer passes in forest operations.

The observed strong reduction of forest floor biomass remaining on skid trail relative to untrafficked areas, with increasing traffic frequency, skid trail slope and degree of curvature, is likely the result of several factors. Forest floor material was likely crushed and mixed with mineral soil during ground-based skidding followed by some displacement or washing out by surface runoff. Further, the amount of litter fall and input to the soil surface may also decrease due to the reduced number of trees and canopy cover over skid trails following tree harvesting (Demir et al. 2007). The impacts of skidding on the litter layer in this study were similar to those shown in other research (Demir et al. 2007, Najafi et al. 2009, Solgi et al. 2014).

Mirroring the direct skidding effect of increased soil compaction, the indirect effects of surface runoff and soil loss also increased with traffic frequency, trail gradient, and switchback curvature, which is consistent with previous findings (Solgi et al. 2014, Solgi et al. 2019a). The 2.9 and 3.1 times greater rates of soil loss in the bare soil treatment (control) in the narrow curves than in wide curves and straight segments, respectively, highlight the importance of skid trail design in ground-based skidding operations, where curvature and switchback position are important determinants of soil compaction (Solgi et al. 2019b). Compared to bare soil (controls) and regardless of switchback curvature, however, mulch cover drastically reduced soil loss in this study, particularly on steep slopes. Sawdust cover was more effective for reducing surface runoff volume and soil loss on both slope classes on straight and curved trail segments than straw mulch. On straight segments, wide curves, and narrow curves, sawdust mulch decreased runoff by 80.2%, 67.3%, and 35.8%, respectively, and sediments by 88.5%, 82.2%, and 75.8%, respectively, while straw mulch decreased runoff by 53.6%, 35.3%, and 24.5% and sediments by 61.9%, 54.6%, and 41.6%, respectively, relative to bare soil. Considering potential differences in soil texture and structure, our results are similar to the 72.8% and 36.5% decrease in runoff volume and the 94.9% and 51.9% decrease in soil losses relative to bare soil following the application of sawdust and straw mulch in a severely compacted loam soil area on straight skid trails in a Hyrcanian forest (Jourgholami and Abari 2017). Similar reductions in soil erosion and loss were reported for a bladed skid trail on bare soil with water bars in the Piedmont of Virginia after the addition of a straw mulch treatment (Wade et al. 2012) or a seed plus mulch treatment, which was followed in effectiveness by the addition of hardwood slash or pine slash (Sawyers et al. 2012). Providing a cover of jute or mulch similarly reduced soil erosion over bare soil under natural rainfall conditions, with best results for the jute cover (Lotfalian et al. 2019).

Unfortunately, due to stolen equipment on site, we were unable to measure the exact amount of each rainfall event in the field, precluding closer investigations of the effectiveness of the protective mulch treatments with rainfall intensity. Nonetheless, averaged across all of the rainfall events, our results confirm that the use of sawdust or straw mulch on skid trails, especially on steep slopes, is an effective method to reduce or prevent runoff and soil loss after skidding (Wade et al. 2012, Masoumian et al. 2017, Lotfalian et al. 2019). Compared to sawdust, the application of agricultural rice straw is not only less effective but has the disadvantage that it may be a conduit to potentially transfer seeds of invasive plant species and pests into the harvested forest area and seems to be more susceptible to wind and water transport and translocation off the skid trail (Vega et al. 2014, Sadeghi et al. 2015). Nonetheless, the addition of a mulch layer is thus an effective closure treatment of skid trails that increases surface roughness, provides immediate cover of the skid trail. Mulch thus protects bare soil by intercepting raindrops, which reduces the velocity and erosive power of the surface water runoff (Ekwue and Harrilal 2010), decreases the detachment and transport of soil particles (Chaplot and Le Bissonnais 2000), enhances infiltration and deposition of sediment (Puustinen et al. 2005), and very effectively delays and reduces runoff generation (Jordán et al. 2010).

5. Conclusion

Building upon previous research that has repeatedly shown that adverse effects of ground-based skidder traffic on soil physical properties in mountainous terrain increase with the frequency of harvesting traffic and the slope gradient (steepness) of the skid trail, this study addressed:

- ⇒ whether, and if so, by how much adverse effects skidding differed between straight trail sections and switchback curves and also whether and how much it depended on the degree of curvature of the switchback curves
- ⇒ whether two different types of soil protective mats applied on skid trails following skidding differentially reduced amounts of surface runoff and soil loss relative to bare soil and whether the ameliorative effects of protective mats differed between straight trail sections and switchback curves and also how much they depended on the degree of curvature.

This study confirmed the variability of adverse effects of skidding on soil physical properties (i.e., dry bulk density, porosity, rutting, forest floor biomass) along the skid trail that increased with traffic frequency, slope gradient, and narrowness of curvature in switchbacks. Research results further indicate ameliorating effects of mulch application following the completion of skidding that effectively reduced the volume of post-skidding surface runoff and soil erosion after trail retirement. Mulch treatments were particularly effective on steep skid trails and especially in narrow curves, where soil erosion rates on unprotected bare soil were very high and mulch provided ready ground cover that increased surface roughness, enhanced soil stability, and reduced soil loss. Rice straw mulch provided less effective soil protection than sawdust mulch due to less weight, which resulted in more convenient transfer and finally less protective cover. As soils are highly susceptible to erosion right after the disturbance, we conclude that mulch should be applied immediately after the skidding operation is completed, which may reduce soil loss by up to 75% over bare soil. As the negative effects of skidding on soil physical properties, the forest floor biomass, rutting, and surface erosion and soil losses were more severe in the switchback curves than on straight skid trail sections, and more so the tighter the curvature, curved portions of the skid trail need to receive particular attention when attempting to minimize adverse effects. We conclude that wider switchback curves should be preferred over narrow curves wherever possible and the application of sawdust mulch on the entire length of the skid trail should be considered as a BMP for trail retirement.

6. References

Abari, M.E., Majnounian, B., Malekian, A., Jourgholami, M., 2017: Effects of forest harvesting on runoff and sediment characteristics in the Hyrcanian forests, northern Iran. European Journal of Forest Research 136(4): 375–386. https://doi.org/10.1007/s10342-017-1038-3

Akbarimehr, M., Naghdi, R., 2012: Determination of most appropriate distance between water diversions on skid trails in the mountainous forest, north of Iran. Catena 88(1): 68–72. https://doi.org/10.1016/j.catena.2011.08.005

Arnaez, J., Larrea, V., Ortigosa, L., 2004: Surface runoff and soil erosion on unpaved forest roads from rainfall simulation tests in northeastern Spain. Catena 57(1): 1–14. https://doi.org/10.1016/j.catena.2003.09.002

Battiato, A., Diserens, E., Laloui, L., Sartori, L., 2013: A mechanistic approach to topsoil damage due to slip of tractor tyres. Journal of Agriculture Science and Applications 2(3): 160–168.

Botta, G., Jorajuria, D., Rosatto, H., Ferrero, C., 2006: Light tractor frequency on soil compaction in the rolling Pampa region of Argentina. Soil and Tillage Research 86(1): 9–14. https://doi.org/10.1016/j.still.2005.01.014

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015: The impact of heavy traffic on forest soils: a review. Forest Ecology and Management 338: 124–138. https://doi.org/10.1016/j.foreco.2014.11.022

Cerda, A., 2007: Soil water erosion on road embankments in eastern Spain. Science of the Total Environment 378(1–2): 151–155. https://doi.org/10.1016/j.scitotenv.2007.01.041

Chaplot, V., Le Bissonnais, Y., 2000: Field measurements of interrill erosion under different slopes and plot sizes. Earth Surface Processes and Landforms 25(2): 145–153. https://doi.org/10.1002/(SICI)1096-9837(200002)25:2<145::AID-ESP51>3.0.CO;2-3

Cristan, R., Aust, W.M., Bolding, M.C., Barrett, S.M., Munsell, J.F., Schilling, E., 2016. Effectiveness of forestry best management practices in the United States: Literature review. Forest Ecology and Management 360: 133-151. https://doi.org/10.1016/j.foreco.2015.10.025

Croke, J.C., Hairsine, P.B., Fogarty, P., 2001: Soil recovery from track construction and harvesting changes in surface infiltration, erosion, and delivery rates with time. Forest Ecology and Management 143(1–3): 3–12. https://doi.org/10.1016/S0378-1127(00)00500-4

Demir, M., Makineci, E., Yilmaz, E., 2007: Investigation of timber harvesting impacts on herbaceous cover, forest floor and surface soil properties on skid road in an oak (*Quercus petrea* L.) stand. Building and Environment 42(3): 1194–1199. https://doi.org/10.1016/j.buildenv.2005.11.008

Ekwue, E.I., Harrilal, A., 2010: Effect of soil type, peat, slope, compaction effort and their interactions on infiltration, runoff and raindrop erosion of some Trinidadian soils. Biosystem Engineering 105(1): 112–118. https://doi.org/10.1016/j.biosystemseng.2009.10.001

Eliasson, L., 2005: Effects of forwarder tyre pressure on rut formation and soil compaction. Silva Fennica 39(4): 549–557.

FAO, Food and Agriculture Organization of the United Nations, 2015: World reference base for soil resources 2014, International soil classification system for naming soils and creating legends for soil maps (Update 2015), World Soil Resources Reports 105, Food and Agriculture Organization of the United Nations, Rome, Italy.

Fernández, C., Vega, J.A., 2016: Are erosion barriers and straw mulching effective for controlling soil erosion after a high severity wildfire in NW Spain? Ecological Engineering 87: 132–138. https://doi.org/10.1016/j.ecoleng.2015.11.047

Freeze, R.A., Cherry, J.A., 1979: Groundwater. Englewood Cliffs (NJ): Prentice Hall, 604 p.

Froehlich, H., Aulerich, D., Curtis, R., 1981: Designing skid trail system to reduce soil impacts from tractive logging machines. Forest Research Laboratory, Oregon State University, Research Paper 44, Corvallis Oregon, USA.

Frey, B., Kremer, J., Rudt, A., Sciacca, S., Matthies, D, Lüscher, P., 2009: Compaction of forest soils with heavy logging machinery affects soil bacterial community structure. Eur. J. Soil. Biol. 45(4): 312–320. https://doi.org/10.1016/j.ejsobi.2009.05.006

Fu, B., Newham, L.T.H., Ramos-Scharron, C.E., 2010: A review of surface erosion andsediment delivery models for unsealed roads. Environ. Environmental Modelling and Software 25(1): 1–14. https://doi.org/10.1016/j.envsoft.2009.07.013

Garcia-Ruiz, J.M., 2010: The effect of land uses on soil erosion in Spain: A review. Catena 81(1): 1–11. https://doi.org/10.1016/j.catena.2010.01.001

Gayoso, J., Iroume, A., 1991: Compaction and soil disturbances from logging in southern Chile. Annals of Forest Science 48(1): 63–71. https://doi.org/10.1051/forest:19910105

Grace, J.M., 2002: Control of sediment export from the forest road prism. Trans. ASAE. 45(3): 1127–1132. https://doi.org/10.13031/2013.9913) @2002

Greacen, E.L., Sands, R., 1980: Compaction of forest soils: a review. Australian Journal of Soil Research 18(2): 163–189. https://doi.org/10.1071/SR9800163

Heninger, R., Scott, W., Dobkowski, A., Miller, R., Anderson, H., Duke, S., 2002: Soil disturbance and 10-year growth response of coast Douglas-fir on non-tilled and tilled skid trails in the Oregon Cascades. Canadian Journal of Forest Research 32(2): 233–246. https://doi.org/10.1139/x01-195

Horn, R., Blackwell, P.S., White, R., 1989: The effect of speed of wheeling on soil stresses, rut depth, and soil physical properties in an ameliorated transitional red-brown earth. Soil and Tillage Research 13(4): 353–364. https://doi.org/10.1016/0167-1987(89)90043-3

Jourgholami, M., Abari, M.E., 2017: Effectiveness of sawdust and straw mulching on postharvest runoff and soil erosion of a skid trail in a mixed forest. Ecological Engineering 109(1): 15–24. https://doi.org/10.1016/j.ecoleng.2017.09.009

Jourgholami, M., Ahmadi, M., Tavankar, F., Picchio, R., 2020: Effectiveness of Three Post-Harvest Rehabilitation Treatments for Runoff and Sediment Reduction on Skid Trails in the Hyrcanian Forests. Croatian Journal of Forest Engineering 41(2): 309–324. https://doi.org/10.5552/crojfe.2020.732

Jourgholami, M., Karami, S., Tavankar, F., Lo Monaco, A., Picchio, R., 2021a: Effects of slope gradient on runoff and sediment yield on machine-induced compacted soil in temperate forests. Forests 12(1): 49. https://doi.org/10.3390/f12010049

Jourgholami, M., Feghhi., J., Picchio, R., Tavankar, F., Venanzi, R., 2021b: Efficiency of leaf litter mulch in the restoration of soil physiochemical properties and enzyme activities in temporary skid roads in mixed high forests. Catena 198: 105012. https://doi.org/10.1016/j.catena.2020.105012

Zemke, J.J., 2016. Runoff and Soil Erosion Assessment on Forest Roads Using a Small Scale Rainfall Simulator. Hydrology 3(3): 25. https://doi.org/10.3390/hydrology3030025

Kalra, Y.P., Maynard, D.G., 1991: Methods and manual for forest soil and plant analysis. Northern Forestry Centre NOR-X-319, Forestry Canada, Northwest Region, Edmonton, Alberta, Canada.

Kinnell, P.I.A., 2016: A review of the design and operation of runoff and soil loss plots. Catena 145: 257–265. https://doi.org/10.1016/j.catena.2016.06.013

Kozlowski, T.T., 1999: Soil compaction and growth of woody plants. Scandinavian Journal of Forest Research 14(6): 596–619. https://doi.org/10.1080/02827589908540825

Lee, J.W., Park, C.M., Rhee, H., 2013: Revegetation of decomposed granite roadcuts in Korea: Developing digger, evaluating cost effectiveness, and determining dimensions of drilling holes, revegetation species, and mulching treatment. Land Degradation and Development 24(6): 591–604. https://doi.org/10.1002/ldr.2248

Li, X., Niu, J., Xie, B., 2014: The effect of leaf litter cover on surface runoff and soil erosion in Northern China. PloS One 9(9): e107789. https://doi.org/10.1371/journal.pone.0107789

Litschert, S.E., MacDonald, L.H., 2009: Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. Forest Ecology and Management 259(2): 143–150. https://doi.org/10.1016/j.foreco.2009.09.038

Lotfalian, M., Babadi, T.Y., Akbari, H., 2019: Impacts of soil stabilization treatments on reducing soil loss and runoff in cutslope of forest roads in Hyrcanian forests. Catena 172(1): 158–162. https://doi.org/10.1016/j.catena.2018.08.023

Martinez-Zavala, L., Jordan-Lopez, A., Bellinfate, N., 2008: Seasonal variability of runoff and soil loss on forest road back slopes under simulated rainfall. Catena 74(2): 73–79. https://doi.org/10.1016/j.catena.2008.03.006

Masumian, M., Naghdi, R., Zenner, E.K., 2017: Effectiveness of water diversion and erosion control structures onskid trails following timber harvesting. Ecological Engineering 105(2): 370–378. https://doi.org/10.1016/j.ecoleng.2017.05.017

McColl, J.G., 1995: Forest clear-cutting soil response, in: Nierenberg W.A., Encyclopedia of Environmental Biology, Vol. 2 (Ed.), Academic Press, San Diego, California, USA, 95–103.

Morgan, R.P.C., 1986: Soil Erosion and Conservation. Longman, New York.

Motavalli, P.P., Anderson, S.H., Pengthamkeerati, P., 2003: Surface compaction and poultry litter effects on corn growth, nitrogen availability, and physical properties of a claypan soil. Field Crops Research 84(3): 303–318. https://doi.org/10.1016/S0378-4290(03)00098-4

Naghdi, R., Solgi, A., Zenner, E.K., 2015: Soil disturbance caused by different skidding methods in north mountainous forests of Iran. International Journal of Forest Engineering 26(3): 212–224. https://doi.org/10.1080/14942119.2015.1099814

Naghdi, R., Solgi, A., Ilstedt, U., 2016a. Soil chemical and physical properties after skidding by rubber-tired skidder in Hyrcanian forest, Iran. Geoderma 265(1): 12–18. https://doi.org/10.1016/j.geoderma.2015.11.009

Naghdi, R., Solgi, A., Labelle, E.R., Zenner, E.K., 2016b: Influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth. European Journal of Forest Research 135(5): 949–962. https://doi.org/10.1007/s10342-016-0986-3

Najafi, A., Solgi, A., Sadeghi, S.H., 2009: Soil disturbance following four wheel rubber skidder logging on the steep trail in the north mountainous forest of Iran. Soil and Tillage Research 103(1): 165–169. https://doi.org/10.1016/j.still.2008.10.003

Najafi, A., Solgi, A., Sadeghi, S.H., 2010: Effects of skid trail slope and ground skidding on soil disturbance. Caspian Journal of Environmental Science 8(1): 13–23.

Nawaz, M.F., Bourrié, G., Trolard, F., 2013: Soil compaction impact and modelling. A review. Agronomy for Sustainable Development 33(2): 291–309. https://doi.org/10.1007/s13593-011-0071-8

Nugent, C., Kanali, C., Owende, P.M.O., Nieuwenhuis, M., Ward, S., 2003: Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. Forest Ecology and Management 180(1–3): 85–98. https://doi.org/10.1016/S0378-1127(02)00628-X

Pacejka, H.B., 2012: Tire and vehicle dynamics, 3rd ed., Butterworth-Heinemann, Oxford, UK.

Picchio, R., Mederski, P.S., Tavankar, F., 2020: How and How Much, Do Harvesting Activities Affect Forest Soil, Regeneration and Stands? Current forestry reports 6(2): 115–128. https://doi.org/10.1007/s40725-020-00113-8

Rivenshield, A., Bassuk, N.L., 2007: Using organic amendments to decrease bulk density and increase macroporosity in compacted soils. Arboriculture and Urban Forestry 33(2): 140–146. https://doi.org/10.48044/jauf.2007.015

Sadeghi, S.H.R., Ghaderi Vangah, B., Safaeeian, N.A., 2007: Comparison between effects of open grazing and manual harvesting of cultivated summer rangelands of northern Iran on in filtration, runoff and sediment yield. Land Degradation and Development 18(6): 608–620. https://doi.org/10.1002/ldr.799

Sadeghi, S.H.R., Gholami, L., Homaee, M., Khaledi Darvishan, A., 2015: Reducing sediment concentration and soil loss using organic and inorganic amendments at plot scale. Solid Earth 6(2): 445–455. https://doi.org/10.5194/se-6-445-2015

Sadeghi, S.H.R., Hazbavi, Z., Kiani Harchegani, M., 2016: Controllability of runoff and soil loss from small plots treated by vinasse-produced biochar. Science of the Total Environment 541(1): 483–490. https://doi.org/10.1016/j.scitotenv.2015.09.068

Sohrabi, H., Jourgholami, M., Jafari, M., Shabanian, N., Venanzi, R., Tavankar, F., Picchio, R., 2020: Soil Recovery Assessment after Timber Harvesting Based on the Sustainable Forest Operation (SFO) Perspective in Iranian Temperate Forests. Sustainability 12(7): 2874. https://doi.org/10.3390/su12072874

Solgi, A., Najafi, A., 2014: The impacts of ground-based logging equipment on forest soil. Journal of Forest Science 60(1): 28–34. https://doi.org/10.17221/76/2013-JFS

Solgi, A., Najafi, A., Sadeghi, S.H., 2014: Effects of traffic frequency and skid trail slope on surface runoff and sediment yield. International Journal of Forest Engineering 25(2): 171–178. https://doi.org/10.1080/14942119.2014.955699

Solgi, A., Naghdi, R., Tsioras, P.A., Nikooy, M., 2015: Soil compaction and porosity changes caused during the operation of Timberjack 450C skidder in northern Iran. Croatian Journal of Forest Engineering 36(2): 77–85.

Solgi, A., Naghdi, R., Labelle, E.R., Tsioras, P.A., Nikooy, M., 2016: Effect of varying machine ground pressure and traffic frequency on the physical properties of clay loam soils located in mountainous forests. International Journal of Forest Engineering 27(3): 161–168. https://doi.org/10.1080/14942119.2016.1226673

Solgi, A., Naghdi, R., Tsioras, P.A., Ilstedt, U., Nikooy, M., Salehi, A., 2017: Combined effects of skidding direction, skid trail slope and traffic frequency on soil disturbance in north mountainous forest of Iran. Croatian Journal of Forest Engineering 38(1): 97–106.

Solgi, A., Naghdi, R., Behjou, F.K., Labelle, E.R., Zenner, E.K., Hemmati, V., 2018: The effects of using soil protective mats of varying compositions and amounts on the intensity of soil disturbances caused by ground-based skidding operations. International Journal of Forest Engineering 29(3): 199–207. https://doi.org/10.1080/14942119.2018.1527174

Solgi, A., Naghdi, R., Labelle, E.R., Behjou, F.K., Hemmati, V., 2019a: Evaluation of Different Methods for Erosion Control on Bladed Machine Operating Trails. Croatian Journal of Forest Engineering 40(2): 319–326. https://doi.org/10.5552/crojfe.2019.532

Solgi, A., Naghdi, R., Zenner, E.K., Tsioras, P.A., 2019b: Effects of ground-based skidding on soil physical properties in skid trail switchbacks. Croatian Journal of Forest Engineering 40(2): 341–350. https://doi.org/10.5552/crojfe.2019.535

Solgi, A., Naghdi, R., Marchi, E., Behjou, F.K., Hemmati, V., 2019c: Assessment of ground-based skidding impacts on physical and chemical properties of forest soils and their effects on maple seedling growth along the margin of the skid trail. Forests. 10(2): 134–150. https://doi.org/10.3390/f10020134

Thawornwong, L., 1996: The effect of skid trail curves on soil loss in a selectively harvested dipterocarp forest in East Kalimantan Indonesia, in: Putz, P.E, Elias, P., Dykstra, D.P., Heinrich, R., Research methods for reduced logging impact: workshop results (Eds.), Center for International Forestry Research (CIFOR), Jakarta, Indonesia, 19–21.

Vega, J.A., Fernández, C., Fonturbel, T., González-Prieto, S., Jiménez, E., 2014: Testing the effects of straw mulching and herb seeding on soil erosion after fire in a gorse shrubland. Geoderma 223–225: 79–87. https://doi.org/10.1016/j.geoderma.2014.01.014

Wallbrink, P.J., Croke, G., 2002: A combined rainfall simulator and tracer approach to assess the role of best management practices in minimising sediment redistribution and loss in forests after harvesting. Forest Ecology and Management 170(1): 217–232. https://doi.org/10.1016/S0378-1127(01)00765-4

Wischmeier, W.H., Smith, D.D., 1958: Rainfall energy and its relationship to soil loss. Transactions, American Geophysical Union 39(2): 285–291. https://doi.org/10.1029/TR039i002p00285

Zar, J.H., 1999: Biostatistical Analysis. 4th Ed. Upper Saddle River, Prentice Hall: 663 p.

Authors' addresses:

Ahmad Solgi, PhD *
e-mail: aforestsolgi@gmail.com
Prof. Ramin Naghdi, PhD
e-mail: rnaghdi@guilan.ac.ir
Department of Forestry
Faculty of Natural Resources
University of Guilan, Somehsara
IRAN

Assoc. prof. Eric K. Zenner, PhD
e-mail: eric.zenner@psu.edu
Penn State University
Department of Ecosystem Science,
and Management
University Park, PA
USA

Ali Masumian, PhD
e-mail: masumian.class@gmail.com
Ramin Shoja, MSc
e-mail: ramin_sh70@yahoo.com
University of Applied Science and Technology
Tehran 1193653471
IRAN

Prof. Farshad Keivan Behjou, PhD
e-mail: farshad.keivan@gmail.com
University of Mohaghegh Ardabili
Department of Natural Resources
Ardabil
IRAN

* Corresponding author

Received: December 08, 2020
Accepted: November 17, 2021