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Research Article

Long-Term Effects of Timber Extraction by a Crawler Tractor on Soil Condition Recovery in a Mixed Forest

Elahe Mohammadi Shahrestani[1], Mehrdad Nikooy[2*], Farzam Tavankar[3], and Hassan Pourbabaei[2]

[1]Ph.D student of Forest Engineering, Dept. of Forestry, Faculty of Natural Resources, University of Guilan, Somehsara, I. R. Iran
[2]Prof., Dept. of Forestry, Faculty of Natural Resources, University of Guilan, Somehsara, I. R. Iran
[3]Asociaeted Prof., Dept. of Forestry, Khalkhal Branch, Islamic Azad University, Khalkhal, I. R. Iran

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Abstract

In this study, the physical, chemical and biological characteristics of compacted soil due to tracked skidding (LTT-100A) after 35 years (from 1986 to 2021) of clear cutting operation were investigated in an even aged mixed deciduous stand in Masal forests, Guilan province, northern Iran. Three levels of machine traffic intensity (TI) (low, LT; medium, MT; and high, HT), two levels of skid trail slope (SC) (Gentle, <10%, GS; and steep, ≥10%, SS), two sample locations(SL) (Between track, BT; and On tracks, OT), and two soil depths (SD) (0-5 cm, and 5-10 cm) were considered as independent variables affecting the process of soil profile recovery. The values measured from the abandoned skid trails were compared with those of undisturbed areas to estimate the soil profile recovery rates. Results showed that TI had significant effects on all soil physicochemical (except for soil moisture) and biological properties (i.e., leaf litter, above-and below-ground biomass); all physicochemical and biological properties (except for soil moisture and leaf litter) were affected by SC; the effect of SL on soil texture, density and moisture was significant; and soil texture and density were the only characteristics affected by SD. The values of soil bulk density and penetration resistance on the skid trails were 35% and 49% higher than those of the control area, respectively, while total porosity value was 17.5% lower than that of the control area. Furthermore, soil organic carbon on the skid trails was 20% less than that of the control area. The amount of soil biomass on the skid trails was not recovered after 35 years, so the above and below ground biomass on skid trails were 42% and 46% less than the control area, respectively. The value of leaf litter on the skid trails was 31% less than that of the control area. Overall, the results of this research revealed that the soil of the studied forest is sensitive to the activity of timber harvesting machines. Thus, sustainable forest management needs to reduce the impact of logging within the context of best management practices (BMP_s).

Keywords: Soil disturbance, soil recovery, skid trail, crawler tractor, log skidding.

1. Introduction

Forest soils are usually vulnerable to improper timber harvesting operation (Picchio et al., 2020). Concerns of soil disturbances through timber harvesting operations using larger, heavier, and more powerful machines have increased over the past decades (Tavankar et al., 2021b). Recovery of forest soils damaged by timber harvesting operations usually takes a long time. The productivity and performance of a forest ecosystem may be affected by damage to the soil during harvesting operations (Jourgholami et al., 2020a, 2020b). Also, several researches have shown that the compaction caused by the traffic of

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∗Corresponding author Tel: +989113388305 Email: nikooy@guilan.ac.ir

harvesting machines has negative effects on the biological properties of the soil such as leaf litter and soil biomass (Naghdi & Solgi, 2014; Venanzi et al., 2016; Picchio et al., 2019; Sohrabi et al., 2019, 2020).

One of the salient features of forest soils is their low bulk density, high porosity and permeability, which make forest soils easily compacted during the movement of harvesting machinery (Lacey & Ryan, 2000). Machines traffic on forest soil induces soil compaction, reduces soil porosity, and condenses the pore connectivity, resulting in an increased soil bulk density and penetration resistance (Williamson & Neilsen, 2000; Marchi et al., 2016; Ebeling et al., 2017; Tavankar et al., 2021a).

Most damage to the soil usually occurs during ground-based skidding (Picchio et al., 2020). Skidding activity transfers compaction pressures both vertically and horizontally to the soil, which results in alteration and damage to the soil structure, soil compaction, and reduction of soil porosity (Picchio et al., 2012; Solgi et al., 2016; Jourgholami et al., 2021a, 2021b).

Compaction of forest soil due to skidding operation is an unavoidable event, although the amount of compaction is entirely related to the type of skidder (i.e., crawler and wheeled), skidder traffic, weight of the load, soil type, trail slope, and soil moisture content during skidding operations. Soil compaction is a major step in the direction of reducing characteristics such as soil pores, penetrability, water and gas conductivity (Picchio et al., 2020). Compacted soil also can negatively impact seedlings height and root growth (Picchio et al., 2019; Tavankar et al., 2021a).

Profitable and sustainable harvesting operation requires modern forestry mechanization. Since the natural recovery of soil properties, especially soil compaction and permeability, is usually very slow and may take decades (Salehi el al., 2012; Sohrabi et al., 2019,2020), determining and mitigating the effect of timber harvesting on forest soils should be a core component of any strategy to achieve sustainable forest management. Recovery of soil physical properties varies and depends on the degree of soil compaction, soil layer depth, soil type, management practices (Hashemi el al., 2021; Hashemi el al., 2020), vegetation and climate condition (Rab, 2004). Ebeling et al. (2017) found that the recovery of compacted forest soils physical properties was partially completed after 20 years at sites with high biological activity and high clay content. According to Tavankar et al. (2022), the full recovery of the chemical and physical properties of the soil requires 20 to 30 years of recovery periods.

Uneven topography, uneven-age stand structure and cost-effectiveness of skidders, compared to other transportation systems, are the main reasons for the development of timber harvesting operation in many natural mountainous forests (Picchio et al., 2020). During tracked skidding, soil particles are rearranged closer together resulting in increased bulk density (mass per unit volume), soil strength (except for soil with low bearing capacities), resistance to penetration, micro-pore proportion but decreased total porosity, infiltration capacity, gaseous exchange, soil aeration, and saturated hydraulic conductivity (Mohieddinne et al., 2019; Jourgholami et al., 2021a,b; Tavankar et al., 2022).

Researches have shown that the amount of above and below ground plant biomass is a suitable growth response to mitigate the effects of soil compaction. In fact, another effect of soil compaction due to the traffic of timber-harvesting machines in the forest is the reduction of plant biomass. Many researches have reported losses in terms of above and below ground plant biomass due to forest soil compaction (Cambi et al., 2015; Jourgholami et al., 2016; Tavankar et al., 2021). Mariotti et al. (2020) reported that the total yield of seedlings had decreased by 12% due to forest soil compaction. Cambi et al. (2015) reported that plant biomass was reduced by 26 % due to soil compaction. Jourgholami et al. (2016) showed that there was a significant inverse correlation between soil compaction and chestnut-leaved oak seedling biomass. A research carried out in Italy (Cambi et al., 2015) revealed an increase in soil compaction by 27% in comparison with undisturbed areas that reduced the Pedunculate Oak (*Quercus robur* L.) seedling performances up to 26% in height and up to 24% in root growth. Tavankar et al. (2021a) reported that complete recovery of above and below ground biomass and total biomass of beech saplings on skid trails requires at least 20 years.

Compaction effect is most distinct in the upper 20 cm of the soil, since the exerted pressure is maximal at the top layers of the soil. It declines with increasing depth as the total pressure is spread out over an enlarging area. Thus, an increase in compaction generally occurs especially in the upper soil layers (Jourgholami et al., 2021a, b).

The long-term impact of timber extraction by a crawler skidder on the soil in a clear-cutting operation has been less studied in the forests of northern Iran. The main purpose of this study was: a) to evaluate the physical and chemical characteristics of the soil and b) to estimate the biomass of herbaceous plants on abandoned skid trails 35 years (1986 to 2021) after skidding by crawler tractor.

2. Materials and Methods

2.1. Study area

The study was conducted in Masal forests in the Hyrcanian forests, northern Iran (37˚06′44″N, 49˚23′31″E) (Figure 1). This study was conducted in the Compartment No 9, which belongs to the District No. 11. The elevation of study area ranged from 350 to 400 m a.s.l.; average annual precipitation is 931 mm with a mean annual temperature of 21.30°C. Deciduous broadleaved forests, with a canopy cover ranging from 70–80%, are mostly composed of hornbeam (*Carpinus betulus* L.), oak (*Quercus castaneifolia* C.A.May.), alder (*Alnus subcordata* C.A.May.), and velvet maple (*Acer velutinum* Boiss.). The clear cutting method was implemented 35 years ago, and about 4,819 m^3 log were extracted from the forest by a steel track skidder LTT-100A (Table 1). Mean skidding distance, mean volume per cycle and mean log number per cycle were 710 m, 3.4 m^3, and 1.9 logs, respectively.

Figure 1. A view of the studied skid trail

Table 1. Technical details of the steel-tracked skidder LTT-100A

Length	6.00 m
Width	2.60 m
Track	3.00 m
Operation power	88.20 kw
Ground unit pressure	0.049 MPa
Track drive sprockets	Cast steel tooth wheel
Pressure in hydraulic systems	14.00 MPa
Number of teeth	9
Width of caterpillar	44.00 cm
Tractor mass	11,200 kg

2.2. Experimental design and data collection

Data was collected in June and July 2021. Three skid trails with gentle and steep longitudinal slopes, each with a length of about

150 m, were randomly selected. There has been no traffic on the selected skid trails after the skidding operations were completed. The first 50 m of the skid trail (close to the log landing) were designated/characterized as a high traffic skid trail (HTS), the middle 50 m as a medium traffic skid trail (MTS) and the final 50 m as a low traffic skid trail (LTS). For each traffic intensity class, two slope classes were distinguished: gentle slope (<10%, GS) and steep slope (≥10%, SS). This classification was based on the longitudinal slope range of the skid trails (5% to 15%) in the study area. Sample plots of 40 m^2 (4 m ×10 m) were installed with a random starting point and at a distance of 5 m between them in each of longitudinal slope class of the skid trail with three repetitions (Figure 2). Four transects perpendicular to the skidding path with random starting point and equal distances of 2 m from each other were placed on each sampling plot (Ezzati et al., 2014). Three transects were randomly selected in each sample plot. To measure the physical, chemical and biological properties of the soil, samples were taken on the skidding paths (i.e., skidding ruts: OR) and the between paths (BR). Three soil samples were taken from each transect to calculate soil bulk density (BD). After removing the litter, soil samples were taken from machine paths from two depths of 0 to 5 cm and 5 to 10 cm using a metal cylinder with a diameter of 5 cm and a length of 5 cm. To measure soil penetration resistance (PR), three samples were taken in each transect using a penetrometer. Finally, 324 soil samples were measured to estimate soil BD (3 TI-traffic intensity×2 SC-slope class×3 P-plot×3 T-transect×3 P-point×2 SD-depth), and 162 PR samples were measured from each skid trail (3 TI-traffic intensity×2 SC-slope class×3 P-plot×3 T-transect×3 P-point). Soil penetration resistance (PR) was measured using a hand-held penetrometer (brand Eijkelkamp, Zevenaar, Netherlands) at the depths of 0 cm, 5 cm, and 10 cm by digging the soil profile.

Soil parameters were analyzed according to the ASTM D854-00 2000 soil laboratory measurement standards. Leaf litter were towed before the collection of the samples. The soil samples at a depth of 10 cm were collected by a soil hammer and rings, put in plastic bags and then labeled. All samples were weighed on the day of collection. Then, they were oven-dried at less than 105◦ C for 24 h. Dry bulk density is calculated as Eq.1:

$$BD = \frac{WD}{VC} \tag{1}$$

where BD is the dry bulk density ($g.cm^{-3}$), WD is the weight of the dry soil (g), and VC is the volume of cylinder (98.125 cm^3).

The total soil porosity (TP) was calculated as Eq. 2 (Picchio et al., 2012):

$$TP = \left[1 - \frac{BD}{2.65}\right] \times 100 \tag{2}$$

where TP is the apparent total porosity (%), BD is the bulk density ($g\ cm^{-3}$), and 2.65 $g\ cm^{-3}$ is the soil particle density measured via pycnometer on the same soil samples used to evaluate the bulk density. Since soil moisture influences the measurement of penetration resistance, all measurements were carried out under similar conditions. Soil pH was determined by an Orion Analyzer Model 901 pH meter in a 1:2.5, soil/water solution, whereas soil organic carbon (OC) was assessed using the Walkley-Black technique (Walkley and Black, 1934).

Leaf litter (forest floor) samples, defined as the O layer from the soil surface to the mineral soil, were also taken by collecting the entire forest floor over a 1 m^2 area from both locations (left and right wheel track) of each plot. Then, the samples were brought to laboratory, oven-dried at 65 °C for 24 h and weighted to determine the leaf litter (Naghdi et al., 2016b). All the herbaceous plants in the litter samples were removed from the soil in a complete form, including the aerial parts and roots, and dried for 24 hours at a temperature of 65 °C in an oven, and then the below-ground and above-ground plant biomass was obtained by weighing the dry matter. Total biomass (TB) was obtained from the sum of above ground (AGB) and below ground (BGB) biomass.

2.3. Analysis of data

Effects of traffic intensity slope of skid trail, soil depth, and sample location on soil physical, chemical and biological properties were analyzed by one-way ANOVA. Normality distribution of data was checked by Kolmogorov-Smirnoff test, and homogeneity of variances among treatments was traced by Levene's test (P=0.05). Duncan's post-hoc test was applied to find statistical differences among treatment means. Correlation between soil physical, chemical and biological properties was analyzed by Pearson correlation test. All data analysis was done by SPSS statistical software of version 19.0 (Chicago, IL, USA). In order to have an overview of all soil characteristics and their recovery rate, percentage differences were used. To calculate the percentage difference between the averages, the average of each variable (without considering traffic class, slope class and depth class) was calculated, and its difference with the average of the control treatment was expressed as a percentage.

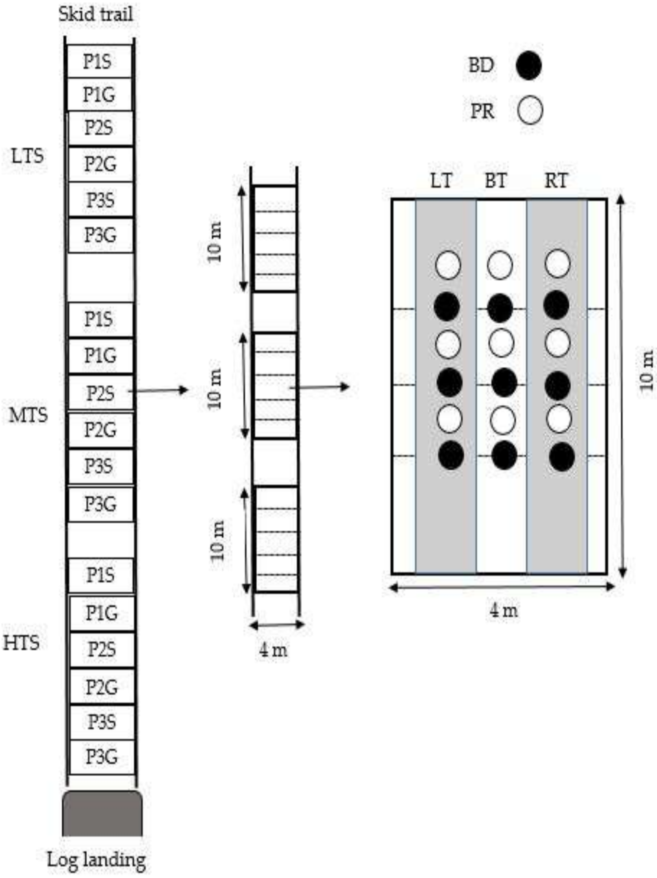

Figure 2. Sketch of the sampling design in skid trails. TS, low traffic skid trail; MST, medium traffic skid trail, HTS, high traffic skid trail; P, plot; S, steep slope, G, gentle slope; BD, bulk density, PR, penetration resistance

3. Results

The results showed that all physical, chemical and biological characteristics of disturbed soils (except soil moisture) were significantly affected by traffic intensity. Skid trail slope had a significant effect on all soil properties (except moisture and leaf litter), soil depth had a significant effect only on soil bulk density and soil penetration resistance, and sample location had a significant effect only on soil physical properties and organic carbon (Table 2).

The highest BD and PR values were observed in high traffic intensities with the lowest values in the control area, while the highest MP and TP was observed in the control area and the lowest values in high traffic skid trails (Table 3). With increasing traffic intensity, the BD and PR increased, while MP and TP decreased. The values of BD and PR in the high traffic skid trails were significantly higher than their values in the medium traffic > low traffic > and control area, while the values of MP and TP in the control area were significantly higher than the low traffic > medium traffic and > high traffic of skid trails.

BD and PR values on the high slope were significantly higher than those on the low slope, while the MP and TP values on the low slope were higher than the high slope of skid trails. The

BD and PR values on machine ruts were significantly higher than those of the between ruts, but the MP and TP values on the between ruts were higher than those on the machine ruts. The amounts of BD and PR values on the 5-10 cm were significantly higher than the 0-5 cm of soil, but the MP and TP values on 0-5 cm of soil depth were higher than those on the 5-10 cm.

Table 2. Results of ANOVA (*F* value) for determining of effects of traffic intensity of machine, slope of skid trail, soil depth, and sample location on the soil physical, chemical, and biological properties in the 35 years old skid

Soil properties	Traffic intensity	Slope of skid trail	Soil depth	Sample location
Physical				
Bulk density	89.41**	22.85**	10.20**	17.22**
Penetration resistance	72.50**	30.74**	17.60**	19.08**
Total porosity	42.45**	24.73**	0.90 $^{N.S}$	19.50**
Moisture content	1.32 $^{N.S}$	1.00 $^{N.S}$	1.05 $^{N.S}$	0.92 $^{N.S}$
Chemical				
Organic carbon	33.19*	22.49**	1.95 $^{N.S}$	14.18**
Electrical conductivity	25.74**	8.42*	1.02 $^{N.S}$	1.00 $^{N.S}$
pH	13.80**	7.99*	0.88 $^{N.S}$	1.40 $^{N.S}$
Biological				
Leaf litter	19.55**	1.10 $^{N.S}$	1.13 $^{N.S}$	0.95 $^{N.S}$
Above ground biomass	22.60**	7.52*	1.21 $^{N.S}$	1.30 $^{N.S}$
Below ground biomass	27.62**	7.33*	0.72 $^{N.S}$	1.72 $^{N.S}$
Total biomass	25.07**	7.50*	0.88 $^{N.S}$	1.60 $^{N.S}$

*indicate significant at α<0.01, ** indicate significant at α<0.01

Table 3. Soil physical properties (mean ± SD) on skid trails after 35 years from skidding operation by crawler tractor and control area. LT = low traffic; MT = medium traffic; HT = high traffic; LS = low slope; HS = high slope; BR = between ruts; OR = on ruts

Treatment	Bulk density (g.cm-^{3})	Penetration resistance (MPa)	Total porosity (%)	Moisture content (%)
Control	0.80±0.04	1.41±0.10	63.05±3.40	63.30±3.75
Traffic intensity				
LT	1.00±0.08 ^{c*}	1.63±0.10 ^{c*}	56.70±3.40 ^{a}	54.02±2.96 ^{a*}
MT	1.09±0.07 ^{b*}	2.10±0.11 ^{b*}	49.11±3.35 ^{b}	53.52±3.65 ^{a*}
HT	1.16±0.08 ^{a*}	2.26±0.10 ^{a*}	40.09±3.26 ^{c}	52.21±3.19 ^{a*}
Slope class				
LS	1.03±0.05 ^{b*}	1.95±0.14 ^{b*}	53.25±3.47 ^{a}	54.12±5.40 ^{a*}
HS	1.12±0.06 ^{a*}	2.16±0.15 ^{a*}	45.05±3.40 ^{b}	52.05±4.57 ^{a*}
Sample location				
BR	1.05±0.06 ^{b*}	2.09±0.10 ^{b*}	57.62±3.89 ^{a}	55.58±3.15 ^{a*}
OR	1.13±0.07 ^{a*}	2.24±0.13 ^{a*}	41.96±3.02 ^{b}	53.75±3.59 ^{a*}
Soil depth (cm)				
0-5	1.03±0.05 ^{b*}	1.95±0.11 ^{b*}	56.20±3.71 ^{a}	53.10±3.62 ^{a*}
5-10	1.11±0.06 ^{a*}	2.22±0.10 ^{a*}	54.61±3.92 ^{a}	52.04±3.08 ^{a*}

Note: different letters after means indicate significant differences between the means of classes in each treatment, and (*) indicate significant differences between the means of classes and control by Duncan's test at α=0.05

The amount of soil moisture contents on the skid trails were not significantly different from those of the control area, but the amount of soil organic carbon on the skid trails was significantly lower than that of the control area (Table 4). The amount of soil electrical conductivity on the control area was significantly higher than the skid trails, while the pH value on the control area was significantly lower than the skid trails. The soil organic carbon and electrical conductivity significantly reduced by increasing traffic intensity and slope of skid trail.

Table 4. Soil Chemical properties (mean ± SD) on skid trails after 35 years from skidding operation by crawler tractor and control area. LT = low traffic; MT = medium traffic; HT = high traffic; LS = low slope; HS = high slope; BR = between ruts; OR = on ruts

Treatment	Organic Carbon (%)	Electrical conductivity (mS.cm^{-1})	Acidity of soil, pH value
Control	4.45±0.15	0.35±0.05	5.45±0.51
Traffic intensity			
LT	3.81±0.19 ^{a*}	0.25±0.05 ^{a*}	6.34±0.39 ^{c*}
MT	3.21±0.11 ^{b*}	0.21±0.04 ^{b*}	7.20±0.45 ^{b*}
HT	2.69±0.10 ^{c*}	0.16±0.10 ^{c*}	8.41±0.36 ^{a*}
Slope class			
LS	3.43±0.20 ^{a*}	0.26±0.04 ^{a*}	6.06±0.43 ^{b*}
HS	3.19±0.11 ^{b*}	0.19±0.05 ^{b*}	7.53±0.40 ^{a*}
Sample location			
BR	3.75±0.06 ^{a*}	0.29±0.06 ^{a*}	6.68±0.43 ^{a*}
OR	3.15±0.07 ^{b*}	0.26±0.05 ^{a*}	6.91±0.31 ^{a*}
Soil depth (cm)			
0-5	3.58±0.05 ^{a*}	0.25±0.11 ^{a*}	6.54±0.22 ^{a*}
5-10	3.41±0.06 ^{a*}	0.23±0.10 ^{a*}	6.62±0.17 ^{a*}

Note: different letters after means indicate significant differences between the means of classes in each treatment, and (*) indicate significant differences between the means of classes and control by Duncan's test at α=0.05

The amount of leaf litter in the control area was significantly higher than skid trails (Figure 3). With increasing traffic intensity, leaf litter significantly decreased. The amount of leaf litter on high slopes was significantly lower than low slopes on skid trails, while it wasn't significantly different in leaf litter values between low and high slopes in control areas.

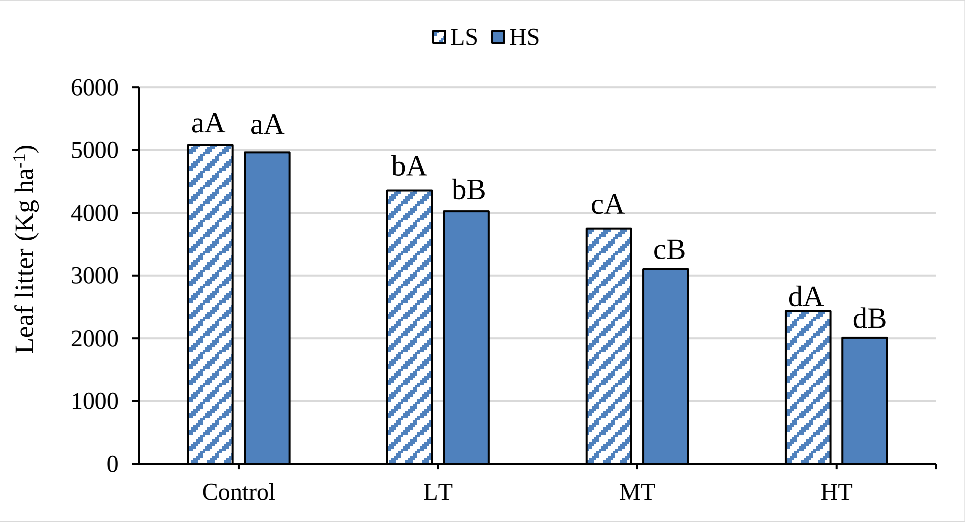

Figure 3. Leaf litter changes under traffic intensity and slope of skid trail. LT, low traffic; MT, medium traffic; HT, high traffic; LS, low slope; HS, high slope. ANOVA results for leaf litter in low slope are F=69.52, P<0.01, and for high slopes are F=71.05, P<0.01. Different lower case letters indicate significant differences between traffic intensities, and capital case letters indicate significant differences between slope classes in each traffic intensity class by Duncan's test at α=0.05

The amount of total biomass (TB) of understory herbaceous on the control area was significantly higher than skid trails (*F*=105.20, *P*<0.01) (Figure 4). Also, both AGB and BGB of understory herbaceous on the control area was significantly higher than skid trails (*F*=80.11, *P*<0.01 for AGB, and *F*=96.13, *P*<0.01 for BGB). All of AGB, BGB and TB of understory herbaceous decreased by increasing traffic intensity. The slope of skid trail had a significant effect on both AGB and BGB of understory herbaceous, so their amounts on low slope class was significantly higher than high slope class.

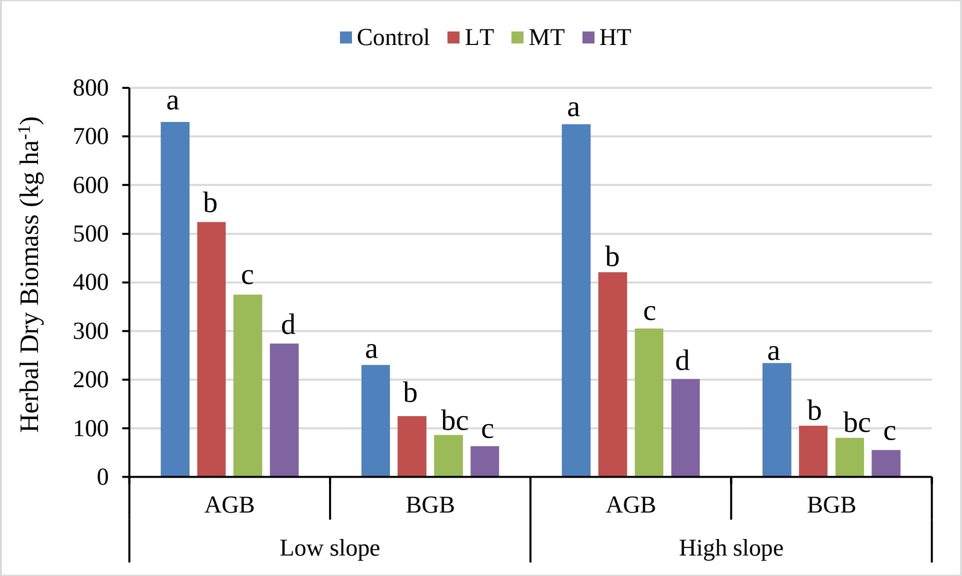

Figure 4. Biomass changes of herbaceous plants under traffic intensity and slope of skid trail. LT, low traffic; MT, medium traffic; HT, high traffic; AGB, above ground biomass; BGB, below ground biomass. Different letter indicates significant differences between means in each biomass section (AGB and BGB) and in each slope class by Duncan's test at α=0.05

Results of correlation analysis indicated that the soil PR significantly correlated with all soil physical, chemical and biological properties; the BD significantly correlated with all soil physical, chemical and biological properties (except moisture content); the TP significantly correlated with all soil physical, chemical and biological properties (except leaf litter); the AGB, BGB, and TB significantly correlated with all soil physical, chemical and biological properties (except moisture content, electrical conductivity, and pH) (Table 5).

Table 5. Correlation coefficient (R^2) between soil properties. BD: bulk density, PR: penetration resistance, MP: micro porosity, TP: total porosity, OC, organic carbon, EC: electrical conductivity, pH: acidity, LL: leaf litter, AGB: above ground biomass, BGB, below ground biomass, and TB: total biomass

	BD	PR	MP	TP	OC	EC	pH	LL	AGB	BGB	TB
BD	1.00	0.842^{**}	0.563^{**}	0.452^{**}	0.522^{**}	0.632^{**}	0.624^{**}	0.331^{**}	0.523^{**}	0.600^{**}	0.421^{**}
PR		1.00	0.291^{*}	0.238^{*}	0.513^{**}	0.428^{*}	0.561^{**}	0.368^{*}	0.638^{**}	0.695^{**}	0.524^{**}
MP			1.00	0.327^{*}	0.396^{*}	0.361^{*}	0.383^{*}	0.117	0.601^{**}	0.631^{**}	0.621^{**}
TP				1.00	0.628^{**}	0.507^{*}	0.461^{**}	0.120	0.552^{**}	0.712^{**}	0.551^{**}
MC					0.061	0.052	0.037	0.051	0.44	0.035	0.041
OC					1.00	0.381^{*}	0.450^{*}	0.354^{*}	0.453^{**}	0.487^{**}	0.264^{*}
EC						1.00	0.463^{**}	0.046	0.022	0.031	0.027
PH							1.00	0.026	0.063	0.076	0.019
LL								1.00	0.762^{*}	0.424^{**}	0.328^{*}
AGB									1.00	0.231	0.858^{**}

BGB	1.00	0.637**
TB		1.00

*Significant at α<0.01, **Significant at α<0.01

Overall, the values of BD, PR, and pH values on the skid trails were higher than their values on the control, and the values of other properties, i.e., MP, TP, MC, OC, EC, LL, AGB, and BGB on the skid trails were lower than their corresponding values on the control areas (Figure 5). The largest difference between skid trail values of PR and control was (+48.9%). The difference in values of pH (+45.6%), BD (+35.1%), BGB (-44.8%), AGB (-41.9%), MP (-28.8%), EC (-31.4%), LL (-31.1%), OC (-20.4%) and TP (-17.5%) between road and control was also significant. In fact, all physical, chemical and biological characteristics of the soil (except MC) of the skid trail were significantly different from the control area.

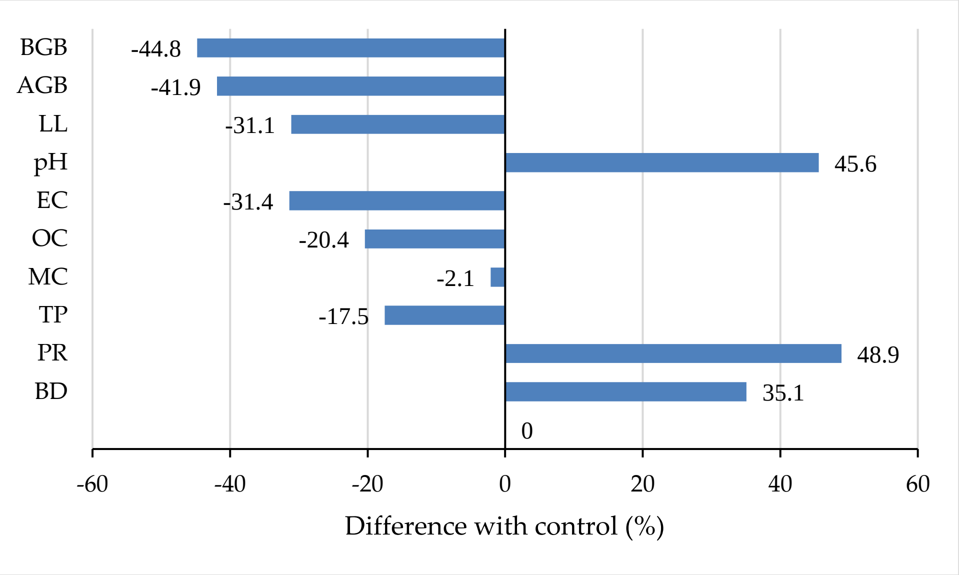

Figure 5. Different values of soil characteristics between the skid trail and the control area 35 years after the time of skidding operations. BD: bulk density, PR: penetration resistance, MP: micro porosity, TP: total porosity, OC, organic carbon, EC: electrical conductivity, pH: acidity, LL: leaf litter, AGB: above ground biomass, and BGB: below ground biomass

4. Discussion

Monitoring the quality of soil environment is one of the most important points in sustainable forest management. In recent decades, the use of powerful and heavy machinery in forest management has rapidly increased (Cambi et al., 2015). In this study, the characteristics of the soil profile disturbed by the tracked-based tractor machine were evaluated 35 years after the skidding operations. Our results showed that the physical and chemical characteristics of disturbed soils did not fully recover, rather they were significantly different from those of the control areas. Similar results related to the lack of recovery of soil properties after a period of 30 years have been reported for harvested forest stands in northern Iran (Tavankar et al., 2021a.b; Jourgholami et al., 2021). Mohieddinne et al. (2019) evidenced that compaction by heavy timber harvesting equipment has a long-term effect on the physical properties of soils; indeed, compaction persists on the fine textured soils that had been compacted 45 years ago, and recovery started from the surface towards the deeper soil layers. Also, the amounts of leaf litter and biomass of plants on the disturbed soil were significantly lower than in the control areas. This result can be due to soil compaction, which makes the growing conditions of plants difficult. On the other hand, it can also be due to the secondary effects of soil compaction such as increased soil erosion along the skid trails, which is consistent with the results reported by Naghdi et al. (2016b). Some natural processes, such as freezing/thawing of soil water, swelling/shrinking of clay particles, root channels in soil, and biological activities arising from soil macro-and-micro-fauna have been suggested as important influences on the natural recovery of soil physical properties (Bottinelli et al., 2014). Ezzati et al. (2012) and Tavankar et al. (2022) demonstrated that more than twenty years are required for BD to fully recover in the upper 10 cm of soil profiles in the Hyrcanian forests of Iran.

The soil penetration resistance and bulk density in the disturbed areas were 49% and 35% higher than those of the control areas after 35 years, respectively. This finding shows that recovery of soil penetration resistance requires more time than the recovery of soil bulk density, while, the values of soil total porosity in the disturbed soils was 17.5% lower than the control areas. The recovery of soil physical properties varies depending on the degree of soil compaction, soil layer depth, soil type, vegetation, and climate condition (Rab, 2004). Therefore, minimizing the area of soil disturbance and the degree of soil compaction during the implementation of harvesting operations is the most important goal of forest managers for the rapid recovery of disturbed forest soils. These results indicate that the physical characteristics of the compacted soils are recovering naturally, although it takes more than 35 years to reach the level of control areas. We found that the amount of soil total porosity on the skid trail was significantly lower than that of the control area. The reduction of total soil pores reduces the gas and water exchange capacity of the compacted soils and may have adverse effects on the activity of soil organisms as well as the physiology of plants.

The results of our research showed that the longitudinal slope of the road and the number of vehicle traffic have a significant effect on the recovery process of compacted soils. Both abiotic and biotic components such as soil microbial populations of forest soil are affected by soil compaction (Bottinelli et al., 2014; Marchi et al., 2016; Picchio et al., 2019, 2020; Jourgholami et al., 2021a,b). The impacts of disturbance caused by timber harvesting equipment such as compaction, rutting, and loss of macropores, can affect coarse soils for decades after harvesting operations (Cambi et al., 2015).

Nevertheless, the biotic and abiotic mechanisms including interactions between roots and soils, clay particle expansions and retractions, soil water freezing and thawing, and macro- and micro-fauna activities can influence and accelerate the recovery of soil properties under natural conditions (Bottinelli et al., 2014, Ebeling et al., 2017; Fründ & Averdiek, 2016). The type of forest operation, the number of machine passes as well as the soil moisture conditions affect damage severity and contribute to control the recovery dynamic (Bygdén et al., 2003; Cambi et al., 2015a,b; Picchio et al., 2018).

Recovery of compacted soils in forest ecosystems is commonly slow and continues for many decades (Ezzati et al., 2014; Cambi et al., 2015; Klaes et al., 2016; Wei et al., 2016; Ebeling et al., 2017), even when freeze-thaw cycles occur (Block et al., 2002). As summarized by Goutal et al. (2013), the measured recovery rates depend on: 1) the different methodologies used to assess natural recovery rate, 2) the original degree of disturbance as a result of soil type, moisture content at the time of traffic, machinery used, etc., and, 3) the processes influencing the recovery rate such as vegetation, biological activity, climate, local variance in topography and geology.

Under natural conditions, for example, in the Amazon Basin, DeArmond et al. (2019) noted that the full recovery of soil did not occur, even 30 years after soil disturbances; however, partial recovery was observed. In the Hyrcanian temperate forests, Jourgholami et al. (2019) found that soil physical properties did not return to pre-compaction levels after a 25-year period of natural reforestation.

Our results indicated that organic carbon on compacted skid trails was significantly lower than control area, which is in line with the findings of Jourgholami et al. (2021b), Khoramizadeh et al. (2021) and Tavankar et al. (2022). We found that soil pH on skid trails was significantly higher (45.6%) than the control area, and this may be due to the higher soil electrical conductivity on the skid trails. Faunal communities are sensitive to the acidity, especially earthworms, which do not tolerate acidic soil profiles (Muys & Granval, 1997; Potthoff et al., 2008; Ebeling et al., 2017). The research by Mohieddinne (2019) showed that the soil type plays an important role in the time required for recover soil compaction, so that

Luvisols need 54 years and Podzols need 70 years to recover soil compaction, if those sandy soils are recovered in less than 20 years due to most biological activities of the soil. In contrast, Ebeling et al. (2017) found that the recovery of physical properties of compacted forest soils was partially completed after 20 years over the sites with high biological activity and high clay content.

Our results showed that the values of AGB and BGB on the road were 41.9% and 44.8% lower than those of the control area, respectively. This can be associated with the higher soil BD of skid trails, compared to the control area. Soil compaction leads to a reduction in the growth of roots and aerial parts of plants, and, consequently, the biomass of plants on the skid trails decreases, compared to the control area. These results are in line with the results of Naghdi et al. (2016b), Picchio et al. (2019), and Tavankar et al. (2022).

5. Conclusion

In this study, the long-term effects of log skidding by crawler skidder on soil physical, chemical and biological properties were investigated after clear cutting operations in mixed deciduous forests. The results showed that traffic intensity and longitudinal slope of the skid trail were the main effective factors on the required time of disturbed soil recovery. The negative effects of machine activity on the soil became apparent even after 35 years from the time of the operation, so that all the soil characteristics of the skidding routes were significantly different with those of the control areas. In general, the results of this research showed that bio-engineering operations such as creating grass lines, brush layers, truncheon cuttings, live check dams, seeding of shrubs, and tree planting are necessary in order to prevent soil erosion and accelerate the natural recovery of soils disturbed by skidder traffic after the harvesting operation.

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مقاله پژوهشی

اثرات بلندمدت خروج چوب با اسکیدر چرخ زنجیری بر بازیابی وضعیت خاک در جنگل‌های پهن برگ ناهمسال

الهه محمدی شهرستانی[1]، مهرداد نیکوی[2*]، فرزام توانکار[3] و حسن پوربابائی[2]

[1]دانشجوی دکتری علوم و مهندسی جنگل، گروه جنگلداری، دانشکده منابع طبیعی دانشگاه گیلان، ایران
[2]استاد گروه جنگلداری، دانشکده منابع طبیعی دانشگاه گیلان، ایران
[3] دانشیار، گروه جنگلداری، دانشگاه آزاد اسلامی، واحد خلخال، خلخال، ایران.

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چکیده

در این مطالعه خصوصیات فیزیکی، شیمیایی و بیولوژیکی خاک‌های کوبیده شده ناشی از تردد اسکیدر چرخ زنجیری ۳۵ سال پس از انجام قطع یکسره در یک توده همسال پهن برگ خزان کننده در جنگل های ماسال در استان گیلان در شمال ایران مطالعه شد. سه کلاسه ترافیک (کم، متوسط و شدید) دو کلاسه شیب مسیر چوبکشی (کمتر از ۱۰ درصد و بیشتر از ۱۰ درصد) در دو موقعیت (روی رد چرخ و بین رد چرخ) و در دو کلاسه عمق (۵-۰ و ۱۰-۵ سانتیمتر) به عنوان متغیرهای مستقل تاثیرگذار بر بازیابی خاک در نظر گرفته شدند. به منظور برآورد نرخ بازیابی خاک مقادیر اندازه گیری شده بر روی مسیرهای چوبکشی با مقادیر مناطق شاهد مقایسه شد. نتایج نشان داد که تیمار ترافیک تأثیر معنی داری بر روی خصوصیات فیزیکی خاک (بجز رطوبت خاک) و خصوصیات بیولوژیکی خاک (مانند عمق لاشبرگ و زیتوده رو و زیر زمینی)، تیمار کلاسه شیب تأثیر معنی داری بر روی خصوصیات فیزیکی-شیمیایی و بیولوژیکی (بجز رطوبت و عمق لاشبرگ)، تیمار موقعیت تأثیر معنی داری بر بافت، جرم مخصوص ظاهری و رطوبت خاک و تیمار عمق خاک تأثیر معنی داری بر روی بافت و جرم مخصوص ظاهری خاک داشت. مقدار جرم مخصوص ظاهری و مقاومت به نفوذ بر روی مسیر چوبکشی به ترتیب ۳۵ و ۴۹ درصد بیشتر از منطقه شاهد، مقدار تخلخل ۱۷/۵ درصد کمتر از منطقه شاهد بود. بعلاوه کربن آلی خاک بر روی مسیر چوبکشی ۲۰ درصد کمتر از منطقه شاهد بود. پس از ۳۵ سال مقدار زیست توده خاک در مسیرهای چوبکشی بازیابی نشد، به طوری که زیست توده رو و زیر زمینی در مسیرهای چوبکشی به ترتیب ۴۲ و ۴۶ درصد کمتر از منطقه شاهد بود. مقدار عمق لاشبرگ در مسیرهای چوبکشی ۳۱ درصد کمتر از منطقه شاهد بود. در مجموع، نتایج این تحقیق نشان داد که خاک جنگل مورد مطالعه به فعالیت ماشین‌های چوبکشی حساس است، بنابراین مدیریت پایدار جنگل نیاز به کاهش تأثیر چوبکشی در چهارچوب بهترین شیوه‌های مدیریتی دارد.

واژه های کلیدی: تخریب خاک، بازیابی خاک، مسیر چوبکشی، اسکیدر چرخ زنجیری، چوبکشی.

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* نویسندهٔ مسئول　　شمارهٔ تماس: ۰۹۱۱۱۳۳۸۸۳۰۵　　ایمیل: mehrdad.nikooy@gmail.com