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Recovery of Soil Bulk Density, Porosity and Rutting From Ground Skidding Over a 20-Year Period after Timber Harvesting in Iran

Sattar Ezzati, Akbar Najafi, M. A. Rab and Eric K. Zenner

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Ground-based skidding can have detrimental effects on soil properties trough soil profile disturbance and compaction that can persist for decades. We investigated the recovery of physical properties of disturbed brown soils on four abandoned downhill skid trails in a deciduous mountain forest in northern Iran. The most recent skidding operations had taken place 1–5 yrs, 6–10 yrs, 11–15 yrs, and 16–20 yrs ago, providing a 20-year chronosequence with four 5-year recovery periods. For each recovery period, mean values for soil bulk density (BD), total porosity (TP), macroporosity (MP), soil moisture content (SM), and rut depth (RD) were assessed for three levels of traffic intensity (Primary (PS), Secondary (SS) and Tertiary (TS) skid trails) and two levels of slope gradients (Gentle (G) and Steep (S)) and compared to those in undisturbed (control) areas. Over the 20-year recovery period, PS trails on gentle slopes exhibited mean values that were 35–42% (BD), 3–7% (SM), and 13–19 cm (RD) greater and 18–24% (TP) and 19–28% (MP) lower compared to undisturbed areas; on steep PS trails, values were 40–46% (BD), 2–13% (SM), and 13–21 cm (RD) greater and 23–27% (TP) and 28–35% (MP) lower, respectively. While RD and SM recovered, 20 years was not long enough for the other physical soil properties, particularly on steep slopes. To minimize soil disturbance, skidding should be confined to areas with gentle slopes and alternative harvesting methods such as cable yarding should be used where slope gradients exceed 20%.

Keywords timber harvesting, soil conservation, skid trail slope, soil disturbance, mountainous forest

Addresses *Ezzati* and *Najafi*, Department of Forestry and Forest Engineering, Tarbiat Modares University, P. Box 64414-356, Iran; *Rab*, Soil Physics Future Farming Systems Research Division, Department of Primary Industries, Victoria, Australia; *Zenner*, Department of Ecosystem Science and Management, Pennsylvania State University, University Park, PA, USA
E-mail a.najafi@modares.ac.ir

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1 Introduction

As with any intervention in natural systems, forestry operations can greatly influence future site conditions. Increased concern has arisen regarding the implications of forest management on the environment, specifically on the forest soil (Grace et al. 2006). Increases in soil disturbance at the time of harvesting can cause a decline in the long-term productivity of the forested landbase (Fox 2000). Maintaining long-term site productivity, however, is essential for sustainable forest management (Ares et al. 2005). A number of authors emphasized that the most important soil physical properties reflecting soil structure degradation are bulk density (Froehlich et al. 1985), pore size distribution or porosity (McNabb et al. 2001), water-holding capacity (Horn et al. 2004) and soil rutting (Eliasson 2005). Changes to these properties often occur simultaneously in the soil matrix and are almost exclusively caused by trafficking of heavy equipment during felling and skidding operations in the cut-block (McNabb 1994). Disturbance and/or removal of surface soil horizons owing to vehicular trafficking results in increasing soil strength, which reduces root growth and moisture availability, and causes nutrient loss over time (Froehlich and McNabb 1983). Decreases in porosity through the elimination of macropores (pores > 0.127 mm in diameter) and the reduction of soil infiltration capacity as well as the rate of water movement into the soils are all associated with compaction from timber harvesting (Murray and Buttle 2004).

Although instances have been reported in which regeneration on primary snig tracks (i.e., a footprint of the skid trail by crawler skidders) was not different from undisturbed areas 12 years after cessation of harvesting in a wet forest of *Eucalyptus sieberi* with high amounts of rainfall in Tasmania (Williamson and Neilsen 2003b), bulk densities remained significantly higher in snig tracks and landings after 17–23 years (Pennington and Laffan 2004) and 25 years after timber harvesting (Rab 1992) in wet forests of SE Australia. Under cool temperate conditions, the consequences of soil disturbance by traffic of harvest machinery can persist for decades in clay loam to silt loam soils (Froehlich et al. 1985, Greacen and Sand 1980, Rab et al. 2004) and recovery processes of soil profiles below wheel tracks may require from 70 to 140 years (Froehlich et al. 1985, Webb et al. 1986).

Recovery rates are variable and are influenced by the slope of skid trails (Najafi et al. 2009), levels of soil compaction, soil type and texture, soil depth, freezing/thawing cycles, moisture and temperature changes, and activities of soil biota (Mace 1971, Thorud and Frissell 1976, Reisinger et al. 1992, Rab et al. 2005, Suvinon 2007, Zenner et al. 2007). Whereas short-term recovery of trafficked soils in forests has been investigated in several studies (e.g., Rab 2004, Zenner et al. 2007), very little information is available on the long-term recovery of physical soil properties and how this recovery might be modified by steep slopes in mountainous areas.

In this study, we address the recovery of physical soil parameters of disturbed brown soils in a deciduous mountain forest in northern Iran over a 20-year recovery period using a chronosequence approach. Specifically, our main objective was to investigate the surface recovery of bulk density, total porosity, macroporosity, soil moisture content, and rutting depth in abandoned skid trails following different traffic intensities on different slope gradients.

2 Material and Methods

2.1 Study Sites

The current research was conducted during August and September 2008 in the northern forests of Iran on land owned by the Necka-Choob Company. The general location of the study sites is between 36°21´19.2˝ and 36°24´15.1˝ N latitude and 53°32´7.4˝ and 53°33´15.8˝ E longitude. Elevation of the study sites ranges from 835 to 1534 m above sea level. The study sites enjoy a mild climate with monthly temperatures ranging from 8 °C in January to 26 °C in July. Mean annual precipitation is 1250 mm, with most precipitation falling in the winter (sometimes in combination with snow) and a minimum in June (but without a real drought period). Relative humidity is generally above 80% (Anonymous 1997).

Table 1. Location and description of the study sites. Four skid trails were selected for study in nearby compartments, one in each of the time since most recent logging classes of 1–5 yrs, 6–10 yrs, 11–15 yrs, and 16–20 yrs. Note that the timber harvest in compartment 91 with a recovery length of 1–5 years was undertaken with a Timberjack 450C skidder, whereas prior harvests in all other compartments were undertaken with a TAF E655 skidder.

Recovery length (compartment number)	Location	Silvicultural system	Forest type	Skid trail length (m)	Elevation (m)
1–5 years (C. 91)	36°21´–36°21´N Lat 53°32´–53°33´E Long	Shelterwood and single tree selection system	*Fagus orientalis, Quercus castanifolia* and *Carpinus betulus*	650	1450–1500
6–10 years (C. 68)	36°21´–36°21´N Lat 53°32´–53°32´E Long	Shelterwood and single tree selection system	*Fagus orientalis, Alnus subcordata* and *Carpinus betulus*	1200	1475–1500
11–15 years (C. 73)	36°21´–36°21´N Lat 53°31´–53°31´E Long	Shelterwood and single tree selection system	*Fagus orientalis, Carpinus betulus, Quercus castanifolia* and *Alnus subcordata*	1300	1407–1470
16–20 years (C. 72)	36°21–36°22N Lat 53°33´–53°33´E Long	Shelterwood and single tree selection system	*Fagus orientalis, Carpinus betulus, Quercus castanifolia* and *Alnus subcordata*	1000	1219–1403

2.2 Sampling Strategy

Table 2. Technical specifications of harvest machinery used in this study.

Specifications	TAF E655	Timberjack 450C
Product group	Wheel skidder	Wheel skidder
Weight (kg)	12000	10257
Number of wheels	4	4
Tire size (mm)	470 X 610	775 X 813
Ground-pressure (kPa)	659	221
Engine power (hp)	65	177
Year of manufacture	1975	1998
Manufacturing location	Romania	Canada

We used existing documents detailing the year of harvest and skid trail maps detailing the position of skid trails in the field provided by the technical forest management office of the Necka-Choob company to select four skid trails previously used for downhill skidding for investigation in this study, one in each of the time since most recent logging classes of 1–5 yrs, 6–10 yrs, 11–15 yrs, and 16–20 yrs (i.e., recovery periods, Table 1). In general, the trails covered on average between 20 to 30% of the cut-block area in each compartment. Because the company upgraded its harvesting equipment within the past 5 years, the rubber-tired TAF E655 skidder was used in timber harvests prior to 6 years ago, whereas more recent timber harvests were performed with the rubber-tired Timberjack 450C model. Thus, confounding harvest location and recovery length with harvest machinery could not be entirely avoided in this study. When comparing results of the shortest recovery time (1–5 yrs) to longer recovery periods (>5 yrs), it must be kept in mind that the plot with the shortest recovery time was also harvested by a skidder with lower ground pressure with potentially lesser harvest traffic effect sizes. A detailed description of harvesting machinery is given in Table 2.

To be included in the study, portions of each skid trail had to be exposed to different harvest

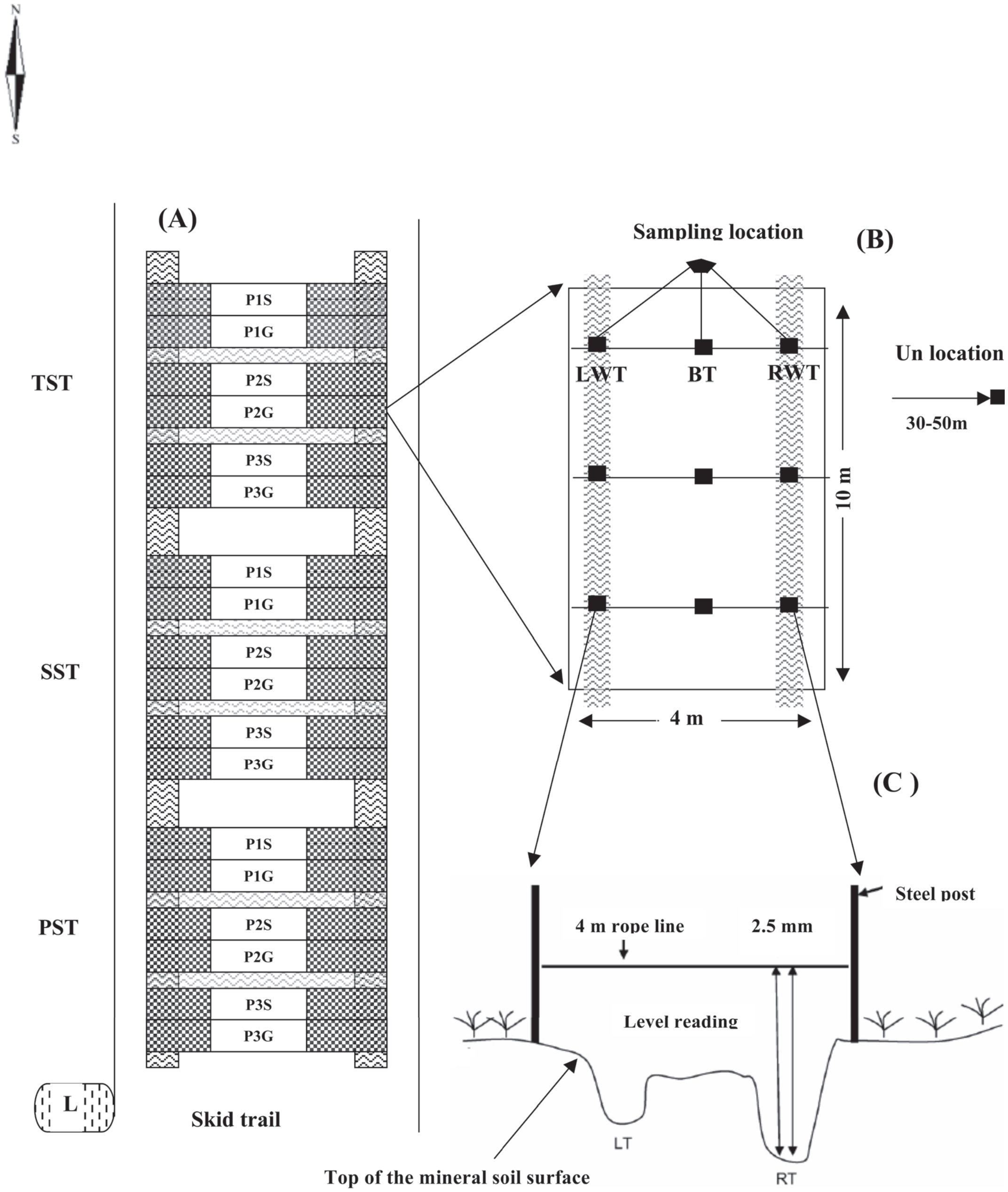

Fig. 1. Sketch of the sampling design. (A) Plot locations along a skid trail with tire tracks shown in treaded imprints underlying the sampling plots. TS = tertiary skid trail, SS = secondary skid trail, PS = primary skid trail, L = log landing. Each skid trail had several replicates of both steep and gentle slopes; P1S = 1st replicate on steep slope, P3G = 3rd replicate on gentle slope. In the field, TS, SS, and PS were different branches of the skid trail and were located much further apart. (B) Enlarged sketch of one sample plot with the dimensions of 10 m by 4 m and the location of the nearby undisturbed control plot (Un) that is associated with each sample plot. LT = left wheel track, BT = between tracks, RT = right wheel track. (C) Sketch of one subplot showing the setup for determining rutting depth.

traffic intensities (i.e., high, medium, and low traffic frequency) and each traffic intensity segment had to further be present on different slope gradients of the same skid trail. Because this is a retrospective study and we do not know the exact number of passes over each point along the skid trail, we used skid trail type as a proxy for traffic intensity. We distinguished three different skid trail types based on the distance from the log landings, the number of branches from the main trail, and expert opinion of the forest manager. Primary skid trails (PS) originated from the log landing and were exposed to a high level of traffic intensity. Secondary skid trails (SS) branched off from a primary skid trail and were exposed to a medium intensity of traffic. Tertiary skid trails (TS) branched off from a secondary skid trail and were exposed to the lowest intensity of harvesting traffic. Two slope gradients were present in each traffic intensity segment of each skid trail: gentle slopes (G) in which the slope gradient of the skid trail was between 0–20% and steep slopes (S) in which the gradient exceeded 20%. Thus, research plots were located in three traffic intensity classes and two slope gradient classes, with three replications of each factor combination (N = 18 in each recovery period, Fig. 1A).

Plots 10 m long by 4 m wide were delineated prior to sampling with buffer zones between plots of at least 5 m to avoid interactions. Soil samples were taken at three locations in each plot: the left wheel track (LT), between the tracks (BT), and the right wheel track (RT) along three randomized lines across the skid trail and perpendicular to the direction of travel, with 2 m buffer zone between lines to avoid interactions (Fig. 1B). Thus, 162 soil samples within 18 sample plots of 40 square meter size were taken in each recovery period for a grand total of 648 soil samples within 72 sample plots. Further, soil samples were taken in nearby undisturbed areas with no skidding impact that were at least 30–50 m away from the skid trail (at least one tree length away from skid road edge) to avoid side effects (N = 54 in each recovery period). The recovery rate of soil properties was determined by comparing mean values of Bulk Density (BD), Total Porosity (TP), Macroporosity (MP), Soil Moisture (SM), and Rut Depth (RD) in each trail to values in nearby undisturbed areas. Here, full recovery of most soil parameters means that there was no statistically significant difference with undisturbed areas; for RD full recovery means that there was no sign of a rut.

2.3 Measurements

To determine bulk density, samples were taken in the surface layer of the mineral soil at a depth of 0–100 mm using soil cores measuring 50 mm in diameter and 105 mm in length. Soil samples were labeled, placed in double plastic bags and taken to the laboratory. The fresh soil samples were promptly weighed, oven-dried at 105 °C for 24 hours, and then weighed again to determine gravimetric soil moisture content. Bulk density was calculated according to Eq. 1 as follows:

$$\mathrm{BD} = \frac{M_s}{V_t} \qquad (1)$$

where BD is the bulk density (g cm^{-3}), M_s is the mass of soil (g), and V_t is the volume of cylinder (cm^3).

To calculate total porosity, first soil particle density was determined using Guy-Lussac pycnometers according to the ASTM D854-00 2000 standard and then Eq. 2 was used as follows:

$$\mathrm{TP} = \frac{1 - \mathrm{BD} / 2.65}{\mathrm{VC}} \qquad (2)$$

where TP is the apparent total porosity (%), BD is the bulk density (g cm^{-3}), 2.65 (g cm^{-3}) is the particle density, and VC is the volume of the intact soil cores (206.06 cm^3).

Macroporosity was determined using the water desorption method (Danielson and Sutherland 1986), whereby the samples were saturated in plastic vats over a period of 5 days, water levels were raised slowly to prevent air entrapment, the samples were then drained for 3 hr, and weights were taken before and after saturation and after drainage (Rivenshield and Bassuk 2007). MP values were computed based on Eq. 3 as follows:

$$\mathrm{MP} = \frac{M_s - M_d}{V} \qquad (3)$$

Table 3. Soil texture classes at a depth of 0–100 mm for skid trails after different recovery lengths since the most recent harvest operation on skid trails with different traffic intensities. Un = Undisturbed area, PS = primary skid trail, SS = secondary skid trail, TS = tertiary skid trail. The range of particle size was <0.002, 0.05–0.002 and 2–0.05 mm for clay, silt and sand, respectively.

Sample site / Recovery length	Soil particle distributions (g 100 g^{-1})			Soil texture
1–5 yr(s)	Clay	Silt	Sand	
Un	28	42	30	Clay loam
TS	34	38	28	Clay loam
PS	50	38	12	Clay
6–10 yrs				
Un	26	38	36	Loam
TS	26	36	26	Loam
PS	34	42	24	Clay loam
11–15 yrs				
Un	28	38	34	Clay loam
TS	36	40	24	Clay loam
PS	30	50	20	Silty clay loam
16–20 yrs				
Un	24	44	22	Clay loam
TS	30	40	30	Clay loam
PS	38	40	21	Clay loam

where MP is the macroporosity (%), M_s is the saturated mass (g), M_d is the drained mass (g), and V is the volume (cm^3) (Danielson and Sutherland 1986).

Soil samples were ground and sieved using a 2.0 mm sieve and particle size distribution was determined using the pipette method (Kalra and Maynard 1991). The description of the soil size distribution in each trail, by traffic intensity, is presented in (Table 3).

Ruts were sampled if they were at least 5 cm deep (measured from the top of the mineral soil surface) and 2 m long (Curran et al. 2009). RD was measured using a profile meter consisting of a set of vertical metal rods (length 500 mm and diameter 5 mm) that are spaced at 25 mm horizontal intervals and slide through holes in a 1 m long iron bar. The bar was placed across the wheel ruts perpendicular to the direction of traffic and roads and positioned to conform to the shape of the depression (Nugent et al. 2003). Average rut depth was calculated using 40 readings on the 1 m bar, considering the top of the mineral soil surface as the level of undisturbed ground (Fig. 1C). The top of the mineral soil surface was determined as close as possible to the outer edge of the left wheel rut in a position that was not visibly disturbed. The starting point for measuring the RD in each rut (left and right) was exactly from this location; along a given plot, this was replicated three times.

2.4 Statistical Analysis

We used a factorial experiment based on a complete block design that included a combination of three factors: recovery length (4 classes), traffic intensity (4 classes including untrafficked control areas), and slope gradient (2 classes); each combination was replicated three times. The data were analyzed using General Linear Models (GLM) and/or two-way ANOVAs in the SPSS 11.5 software. To characterize soil recovery over time, mean values of physical soil properties at each plot were compared to those in undisturbed (untrafficked) areas near each trail using Tukey's multiple range test (HSD) (Zar 1999). One-way ANOVA (significance test criterion $P \leq 0.05$) was used to compare the physical soil properties in the three traffic intensity and the two slope classes (main effects) with those in undisturbed areas separately within each recovery period. Paired *t*-tests were used to analyze soil property data in two slope gradients for each recovery period at an alpha level of 0.01. Traffic intensity by slope gradient combinations with no significant differences in physical soil properties to untrafficked areas were considered to have fully recovered.

3 Results

3.1 Bulk Density (BD)

Physical soil properties in all recovery periods, with the exception of SM in the 6–10-year recovery period were statistically significantly affected by harvest traffic intensity, sometimes in interaction with the soil gradient (Tables 4–6). Slope gradient also affected physical soil properties in different recovery periods, but the effect was less consistent (Tables 4–6).

Mean BD was significantly affected by traffic intensity and slope gradient in most recovery periods (Table 4). BD increased considerably with increasing traffic intensity levels (Fig. 2). Compared to undisturbed areas, all trafficked areas (with the exception of TS on gentle slopes in the 11–15-year recovery period) showed greater BD values, regardless of slope gradient or the length of recovery (but not all were statistically significantly different, Tables 5 and 6). Mean BD values were generally greater on PS and SS trails compared to TS trails and greater on steep slopes than gentle slopes, but exceptions occurred. There was no sign of a systematic recovery over the 20-year chronosequence in the more intensively trafficked skid trails on either slope gradient. Although lower BD values in TS trails hinted at a recovery starting after 6–10 years, large increases in BD values in the 11–15-year period indicated that the recovery was not sustained. Even after a 20-year recovery length, BD values of 1.44 g cm^{-3} were observed on PS trails, which still exceeded values in untrafficked areas by 51%.

Table 4. *P*-values based on analysis of variance (GLM) of different physical soil properties for different recovery lengths as a function of traffic intensity (3 classes plus untrafficked controls), slope (2 classes), and their interaction. BD = bulk density, TP = total porosity, MP = macroporosity, RD = rutting depth, and SM = soil moisture; df = degrees of freedom.

Soil property	Recovery length (yrs)	Traffic (3 df)	Slope (1 df)	Traffic × slope (3 df)
BD (g/cm^{-3})	1–5	0.002	0.770	0.700
	6–10	<0.001	<0.001	0.473
	11–15	0.825	<0.001	0.006
	16–20	<0.001	0.296	<0.001
TP (%)	1–5	<0.001	0.210	0.115
	6–10	<0.001	<0.001	0.473
	11–15	0.825	<0.001	0.006
	16–20	0.000	0.296	<0.001
MP (%)	1–5	0.146	0.286	0.484
	6–10	<0.001	0.442	0.875
	11–15	0.009	0.569	<0.001
	16–20	<0.001	0.009	<0.001
SM (%)	1–5	0.670	0.001	0.58
	6–10	0.697	0.35	0.155
	11–15	0.000	0.35	0.022
	16–20	0.231	0.13	0.765
RD (cm)	1–5	<0.001	0.387	<0.001
	6–10	<0.001	0.062	0.187
	11–15	<0.001	0.003	0.860
	16–20	-	-	-

Table 5. Means ± standard errors of different physical soil properties by recovery length since the last timber harvest for skid trails exposed to different traffic intensities on two different slope classes. BD = bulk density, TP = total porosity, MP = macroporosity, RD = rutting depth, and SM = soil moisture; Un = undisturbed area, TS = tertiary skid trail, ST = secondary skid trail, PS = primary skid trail, 0 = rutting depth in undisturbed area, and FR = full recovery. Different letters indicate statistically significant differences within rows among traffic intensities and slope classes in each recovery period at the alpha = 0.01 level based on analysis of variance (GLM).

Soil property	Recovery length (yrs)	Slope classes						
				< 20%			> 20%	
		Un	TS	SS	PS	TS	SS	PS
BD	1–5	0.98±0.11^{c}	1.16±0.20^{ab}	1.29±0.03^{ab}	1.37±0.07^{a}	1.22±0.03^{ab}	1.25±0.03^{ab}	1.38±0.08^{a}
(g cm^{-3})	6–10	0.98±0.05^{c}	0.99±0.04^{dc}	1.17±0.04^{bc}	1.24±0.05^{b}	1.11±0.04^{bc}	1.29±0.04^{ab}	1.47±0.04^{a}
	11–15	0.96±0.04^{c}	1.32±0.09^{ab}	1.16±0.07^{bc}	1.20±0.11^{bc}	1.28±0.09^{ab}	1.45±0.03^{a}	1.47±0.11^{a}
	16–20	0.95±0.04^{c}	1.05±0.06^{c}	1.39±0.04^{ab}	1.39±0.05^{ab}	1.36±0.05^{ab}	1.16±0.06^{bc}	1.44±0.05^{a}
TP (%)	1–5	63.0±1.38^{a}	56.2±2.51^{ab}	51.50±1.46^{c}	48.30±3.35^{c}	53.80±1.23^{bc}	51.90±2.74^{c}	47.90±1.98^{c}
	6–10	71.10±3.12^{a}	62.60±1.16^{ab}	56.00±1.62^{bc}	53.30±1.86^{c}	58.00±1.15^{bc}	51.20±1.40^{cd}	44.40±1.58^{d}
	11–15	57.60±0.53^{a}	50.00±2.48^{bc}	56.10±1.05^{ab}	54.90±1.91^{ab}	51.60±2.51^{bc}	45.20±1.46^{c}	44.40±1.59^{c}
	16–20	62.7±1.27^{a}	60.50±2.16^{a}	47.50±1.39^{c}	47.70±1.84^{c}	48.70±1.71^{bc}	54.50±2.28^{ab}	45.70±2.01^{bc}
MP (%)	1–5	53.90±0.88^{a}	42.0±2.36^{b}	40.30±1.88^{b}	38.00±3.39^{b}	42.20±1.32^{b}	45.50±2.42^{ab}	38.60±3.01^{b}
	6–10	44.60±1.84^{a}	43.30±1.94^{ab}	35.70±1.92^{bc}	34.00±1.83^{c}	43.50±1.54^{ab}	36.90±1.69^{bc}	36.30±2.10^{bc}
	11–15	44.90±1.31^{a}	35.60±2.12^{bc}	38.0±1.05^{ab}	36.90±1.34^{b}	43.00±2.76^{ab}	28.40±1.49^{c}	36.30±2.12^{b}
	16–20	49.70±0.93^{ab}	50.60±2.17^{a}	37.0±1.35^{cd}	35.10±1.92^{d}	36.60±1.36^{cd}	43.10±1.92^{bc}	32.10±1.67^{d}
SM (%)	1–5	19.62±1.14^{b}	29.54±3.65^{a}	23.05±1.57^{b}	21.33±0.77^{b}	23.92±5.06^{b}	14.76±0.81^{b}	19.24±2.60^{b}
	6–10	36.52±1.30^{a}	39.83±3.78^{a}	44.73±3.72^{a}	39.81±4.51^{a}	29.93±1.61^{a}	29.51±2.63^{a}	36.78±0.97^{a}
	11–15	24.09±1.47^{bc}	24.96±1.56^{bc}	37.27±2.33^{a}	30.34±2.71^{ab}	17.60±1.92^{c}	34.91±2.18^{a}	35.82±1.27^{a}
	16–20	24.92±1.01^{a}	20.51±0.81^{a}	21.79±0.71^{a}	26.02±3.45^{a}	25.19±1.49^{a}	27.33±4.28^{a}	28.18±1.96^{a}
RD (cm)	1–5	0	8.29±0.39^{d}	10.70±0.28^{cd}	17.30±1.37^{b}	11.90±0.72^{c}	12.40±0.52^{c}	20.90±0.64^{a}
	6–10	0	< 5 (FR)	10.00±0.67^{bc}	12.60±0.91^{ab}	7.20±0.40^{c}	10.40±0.45^{bc}	15.30±1.81^{a}
	11–15	0	11.90±1.10^{ab}	8.2.00±1.10^{c}	12.40±1.28^{ab}	12.20±0.09^{a}	9.50±0.45^{bc}	14.20±0.45^{a}
	16–20	0	< 5 (FR)	< 5 (FR)	11.20±0.52^{a}	< 5 (FR)	< 5 (FR)	13.60±0.77^{a}

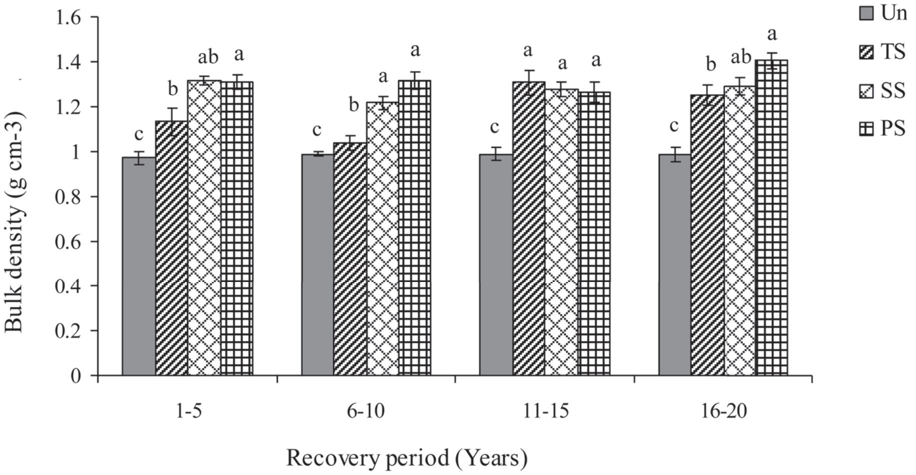

Fig. 2. Means and standard errors of bulk density in skid trails exposed to different traffic intensities by length of recovery (years since the most recent harvest). Different letters indicate statistically significant differences among traffic intensities and recovery periods.

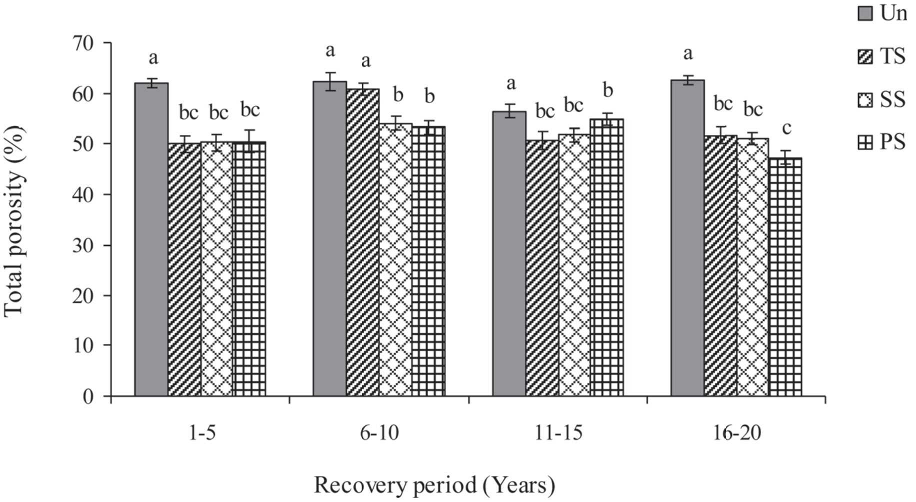

Fig. 3. Means and standard errors of total porosity in skid trails exposed to different traffic intensities by length of recovery (years since the most recent harvest). Different letters indicate statistically significant differences among traffic intensities and recovery periods.

3.2 Total Porosity (TP)

Mean TP was significantly affected by traffic intensity and slope gradient in most recovery periods (Table 4). TP was generally reduced with increasing traffic intensity and skid trail slope in all recovery periods, but the effect was not always statistically significant (Table 5). Despite some large inherent variability of TP among the different recovery periods even in the undisturbed areas, TP was lower in the trafficked areas, with lowest TP values generally observed in the PS trails (Fig. 3). Although TP values in TS trails on gentle slopes were similar to those observed in untrafficked areas after a recovery period of 16–20 years, no recovery was observed for the other skid trails on either slope gradient (Table 6). After a 16–20-year recovery period and averaged across slope gradient, TP was more than 10% lower in skid trails compared to untrafficked areas, with no significant differences among skid trails exposed to different traffic intensities (Fig. 3).

3.3 Macroporosity (MP)

Mean MP was significantly affected by traffic intensity and slope gradient in most recovery periods (Table 4). With the exception of TS trails on gentle slopes in the 6–10 and 16–20-year recovery periods, MP values were considerably lower in trafficked areas compared to undisturbed areas in all periods and for both slope gradients (Fig. 4, Tables 5 and 6). Although MP values were generally lowest in the PS trails on both slope gradients, this was not always the case. Further, MP values were not consistently lower on steep slopes compared to gentle slopes. Although MP values in TS trails on gentle slopes were similar to those observed in untrafficked areas after a recovery period of 6–10 and 16–20 years, no systematic recovery over time was observed for the other skid trails on either slope gradient. After a 16–20-year recovery period and averaged across slope gradient, MP was more than 10% lower in skid trails compared to undisturbed areas, with lowest MP values observed in PS trails (Fig. 4).

3.4 Soil Moisture (SM)

Mean SM was generally not significantly affected by traffic intensity, slope gradient, and their interactions, but exceptions occurred (Table 4). Relative to undisturbed areas, SM sometimes increased with increasing traffic intensity, especially for SS and PS, but this increase was very inconsistent (Fig. 5). Compared to undisturbed areas, the largest increase in SM was observed for SS and PS after a 11–15-year recovery period and had essentially reached its maximum on steep slopes (Tables 5 and 6). After a recovery period of 20 years, SM had fully recovered in TS, SS and PS trails on both slope gradient classes (Table 5).

Table 6. Means ± standard errors of different physical soil properties by recovery length since the last timber harvest for skid trails on two different slope classes and averaged over traffic intensity. BD = bulk density, TP = total porosity, MP = macroporosity, RD = rutting depth, and SM = soil moisture; Un = undisturbed area, TS = tertiary skid trail, ST = secondary skid trail, PS = primary skid trail, and 0 = rutting depth in undisturbed area. Different letters indicate statistically significant differences within rows between the two slope classes in each recovery period at the alpha = 0.01 level based on paired *t*-tests.

Soil properties	Recovery period (yr)											
	1–5			6–10			11–15			16–20		
	Un	<20%	>20%	Un	<20%	>20%	Un	<20%	>20%	Un	<20%	>20%
BD (g cm^{-3})	0.97 ± 0.12^{b}	1.20 ± 0.04^{a}	1.29 ± 0.14^{a}	0.98 ± 0.00^{c}	1.13 ± 0.03^{b}	1.28 ± 0.03^{a}	1.12 ± 0.03^{c}	1.20 ± 0.03^{b}	1.40 ± 0.03^{a}	0.99 ± 0.03^{b}	1.30 ± 0.03^{a}	1.30 ± 0.03^{a}
TP (%)	63.0 ± 0.02^{a}	53.00 ± 0.02^{b}	51.0 ± 0.02^{b}	65.00 ± 0.02^{a}	57.00 ± 0.01^{b}	52.00 ± 0.01^{c}	58.00 ± 0.01^{a}	54.00 ± 0.01^{b}	46.00 ± 0.01^{c}	63.00 ± 0.01^{a}	50.00 ± 0.01^{b}	50.00 ± 0.01^{b}
MP (%)	53.90 ± 0·9a	40.50 ± 1.04^{b}	42.1 ± 1.05^{b}	44.60 ± 1.08^{a}	37.60 ± 1.20^{b}	39.00 ± 1.1^{b}	44.90 ± 1.30^{a}	36.80 ± 0.90^{b}	34.20 ± 1.50^{b}	49.70 ± 0.90^{a}	39.00 ± 1.40^{b}	37.50 ± 1.10^{b}
SM (%)	19.60 ± 1.14^{ab}	25.30 ± 1.68^{a}	19.3 ± 2.01^{b}	37.20 ± 1.14^{a}	36.88 ± 1.97^{a}	31.60 ± 1.24^{a}	24.10 ± 1.45^{b}	32.00 ± 1.61^{a}	32.10 ± 1.70^{a}	24.70 ± 0.98^{a}	23.10 ± 1.39^{a}	26.60 ± 1.55^{a}
RD (cm)	0	13.30 ± 1.41^{a}	13.1 ± 0.53^{a}	0	11.01 ± 0.59^{a}	10.10 ± 0.69^{a}	0	9.10 ± 0.92^{b}	11.30 ± 0.48^{a}	0	11.20 ± 0.52^{a}	13.60 ± 0.77^{a}

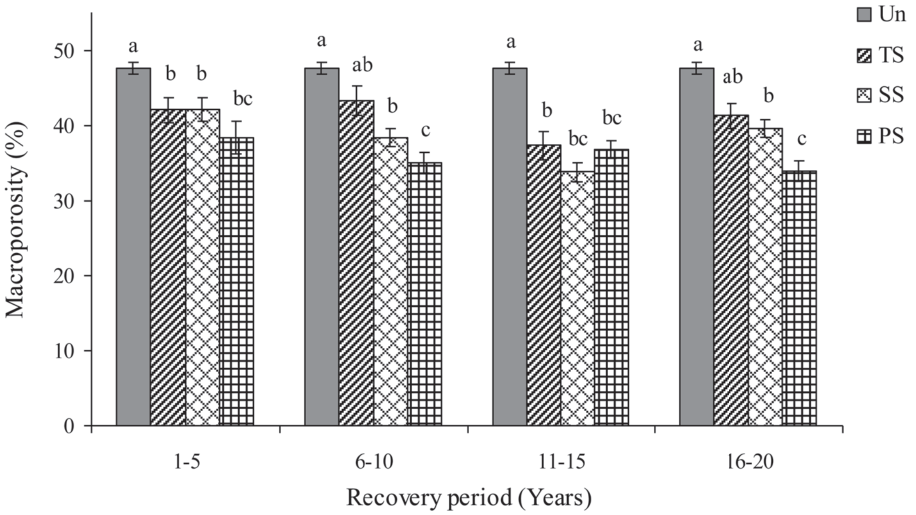

Fig. 4. Means and standard errors of macroporosity in skid trails exposed to different traffic intensities by length of recovery (years since the most recent harvest). Different letters indicate statistically significant differences among traffic intensities and recovery periods.

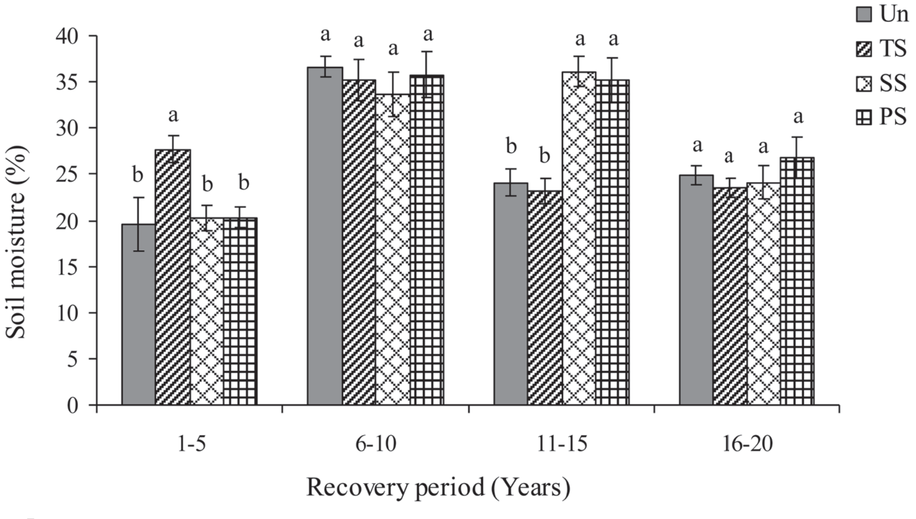

Fig. 5. Means and standard errors of soil moisture content in skid trails exposed to different traffic intensities (excluding undisturbed areas) by length of recovery (years since the most recent harvest). Different letters indicate statistically significant differences among traffic intensities and recovery periods.

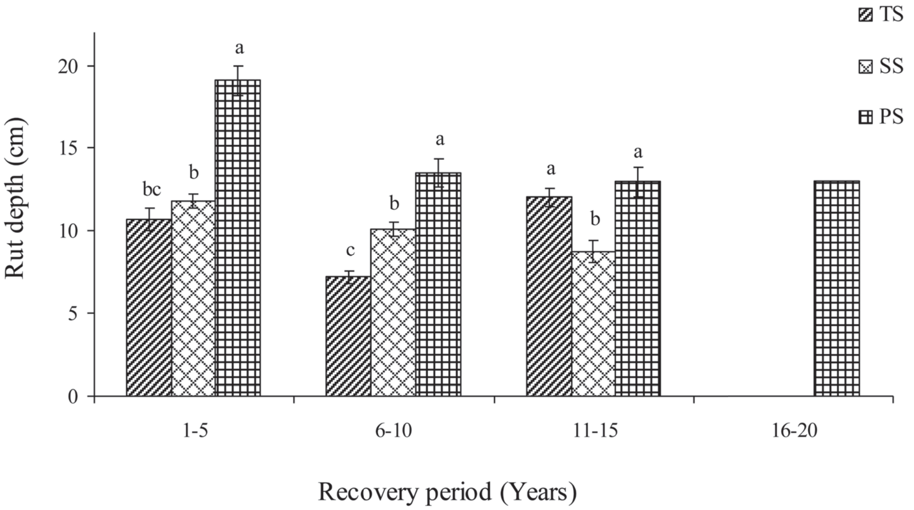

Fig. 6. Means and standard errors of rutting depth in skid trails exposed to different traffic intensities (excluding undisturbed areas) by length of recovery (years since the most recent harvest). Different letters indicate statistically significant differences among traffic intensities and recovery periods.

3.5 Rut Depth (RD)

RD increased considerably with increasing traffic intensity, with RD generally greater in PS than SS and TS trails (Table 5, Fig. 6). The greatest RD of 21 cm was recorded for PS trails on steep slopes after a recovery period of 1–5 years (Table 5). Averaged over traffic intensity, mean values of RD were generally not significantly different between slope gradients in any recovery period, with the exception of the 11–15-year period (Table 6). After a recovery period of 20 years, RD had fully recovered in TS and SS trails on both slope gradient classes. RD also decreased significantly on PS trails after 20 years, but RD was still 11 and 14 cm on gentle and steep slopes, respectively (Table 5).

4 Discussion

4.1 Bulk Density

Mean BD values in the topsoil layer of skid trails increased with increasing traffic intensity and slope gradient and generally did not recover to levels seen in nearby undisturbed areas even after 20 years. The lack of recovery was particularly evident in the heavily trafficked skid trails, where BD was still around 40% higher compared to undisturbed areas, but even lesser trafficked tertiary skid trails showed elevated BD values, particularly on steep slopes. Although the partial recovery and decrease of BD on gently sloped tertiary skid trails may be due to a lesser degree of initial soil compaction and/or fewer passes as well as a larger concentration of the forest floor mass on the trail surface layers (Greacen and Sands 1980, Rab 2004), it is also conceivable that the low BD values observed in the 6–10 and 16–20-year recovery periods, but not in the 11–15-year period, may not necessarily reflect a true recovery. Although these low BD values are consistent with the higher TP and MP values that were similarly observed in these tertiary skid trails in the same recovery periods, it should be remembered that the observed recovery could partly be an artifact of our sampling in spatially different locations using a chronosequence approach.

Nonetheless, our BD results are in keeping with previous studies that have demonstrated that more than twenty years are required for BD to recover in the upper 100 mm of soil (Jakobsen 1983, Webb 2002, Rab 2004). The 40% increase in BD values on primary skid trails remaining after a recovery period of 20 years in this study is comparable to a 51% increase remaining after a 10-year recovery period (Rab 2004), a 54% increase remaining after a 25-year recovery period (Anderson et al. 1992), and a 29% increase remaining after a 17–23-year recovery period (Pennington et al. 2003) observed in other studies. Our BD results are further consistent with results from a Krasonozem soil in southeastern Australia, where compaction was still detectable in the surface 30 cm 32 years after harvesting (Jakobsen 1983). Differences in the recovery rates of BD have been associated with differences in slope gradient of skid trail, type of the skidding machinery, soil texture, initial bulk density, soil moisture content at time of operations, the activity of soil fauna and flora, and local climatic conditions (Block and VanRees 2002, Rab 2004). It seems clear, however, that in the absence of ameliorative treatments the recovery of BD in the upper 100 mm of disturbed soils in our forests caused by harvesting operations is a very slow process that may take several decades to return to pre-harvest levels, as has been reported elsewhere (Jakobsen 1983, Webb 2002, Rab 2004).

Although BD values were sometimes, but not always, greater on steeper slopes in this study when compared with more gentle slopes, increasing skid trail slope can cause increased disturbance in both extent and depth of surface soil on the skid trail (Krag et al. 1986, Najafi et al. 2009). The current study confirmed that both traffic intensity and skid trail slope can affect the extent of soil disturbance as well as the speed of recovery, but the effects are not straightforward.

The lack of statistically significant differences of BD between the two slope gradient classes within each traffic intensity class in the 1–5-year recovery period may be explained by the exposed bedrock layer and shallow soil depth on the site as well as the use of the Timberjack on this site, which exerts a much lower ground pressure on the soil surface than the TAF skidder that was used in the other sites (Table 2).

A stable state of compaction (BD) over time, as shown in this study, can vary with several factors such as trail slop gradient, soil texture and initial levels of compaction (Lacey and Ryan 2000, Powers et al. 2005), with potentially detrimental effects on long-term tree growth and stand productivity. For example, significant reductions of average tree and stand total volume of up to 28% following litter and topsoil removal and/or moderate subsoil compaction, with a further reduction of up to 38% following heavy compaction were documented in a radiata pine plantation 26 years after planting (Murphy et al. 2009).

4.2 Total Porosity

The partial recovery of TP on gently sloped tertiary skid trails is consistent with the recovery of BD and may be similarly ascribed to a lesser degree of initial compaction, lower traffic intensity, lower soil moisture content at the time of the harvest operations or a higher concentration of forest floor material on the skid trail with a correspondingly higher bioturbing activity (Block and VanRees 2002, Miller et al. 2004, Ares et al. 2005, Makineci et al. 2007). Nonetheless, a 20-year recovery period was insufficient for TP to approach values observed in undisturbed areas, particularly on primary skid trails, where TP were still about 15% lower. Blouin et al. (2005) similarly observed that the lowest total porosity remained on landings and primary trails soils after a 23-year recovery period.

Despite some exceptions, TP generally decreased with an increasing slope gradient of the skid trail. Decreases of TP on steep slopes may be associated with a lower skidder speed on steeper slope terrain due to decreased traction of the machinery (Kozlowski 1999, Najafi et al. 2009). Thus, the top soil is vibrated more and is exposed to more disturbances compared to trails on flatter terrain. Consequently, recovery of TP may also be delayed on steeper slopes, and future decreases in forest site productivity and increases in the potential for erosion and changed landscape hydrology may be unavoidable because of increases in bulk density and corresponding decreases in air-filled porosity until only trapped air remains in the soil pores (McNabb et al. 2001, Williamson and Nielsen 2003a).

4.3 Macroporosity

Analogous to findings in other studies (Rab 1996, Blouin et al. 2005), MP values decreased significantly with increasing traffic intensity and, to a minor extent, with an increasing slope of the skid trails. During timber harvesting operations, soil particles are rearranged and the continuity of pore spaces of both micro-and macro-pores may collapse. When air filled porosity falls below 10% of the total soil volume, microbial activity can be severely limited in most soils (Brady and Weil 2001). Although MP values were above this critical level of 10% in the present study, MP, which plays the most important role for site productivity, had not recovered to values similar to undisturbed areas after 20 years. Once again, tertiary skid trails on gentle slopes, whose MP values in the 6–10 and 16–20-year recovery periods were not different from undisturbed areas, were a notable exception. It is unclear, however, whether this recovery was associated with a lower traffic volume, higher soil fauna activity, more soil shrinking and swelling (Worrell and Hampson 1997, Greacen and Sand 1980, Rab 2004) or was due to our sampling scheme.

Decreases in MP can cause poor aeration, reduce permeability to water, produce waterlogged conditions as well as inhibit gaseous exchange between soil and air (Greacen and Sands 1980, Rab 1992). This may result in decreased tree growth because of reduced root penetration and biological and metabolic activity in the disturbed soil profile (Froehlich and McNabb 1983, Ampoorter at al. 2007). The consequences of increased compaction and reduced macroporosity on ecosystem processes and function are complex and often hidden for several years. For example, whereas initial seedling germination may be high in the first year after harvesting, seedling death after a number of years has been related to the mechanical interference to root growth and moisture deficiency and aeration stresses in compacted, exposed soil (Cremer 1969, Williamson and Neilsen 2003b).

Nonetheless, neither MP nor TP and BD showed any recovery over a 20-year period compared to undisturbed baseline values and will require significantly more time to fully recover. This is in contrast to findings by McNabb et al. (2001), who reported that a fine to medium texture luvisol showed a significant recovery in the soil's pore size distribution after only one year of recovery from harvesting operations with three skidding cycles. This difference to our results may be attributed to differences in soil texture as well as cooler climatic conditions of boreal forests. It has been proposed that the most rapid rate of soil recovery occurs in areas with cold winters and high rainfall under wet conditions, where freeze/thaw cycles may loosen soil pores (Ziegler et al. 2006). In Iran's mountain forests, where annual mean temperatures are much higher (in this study they vary between 18 and 24 °C with mean annual of rainfall 1250 mm), less intense freeze/thaw and wetting/drying cycles in shallow soils may partly explain a slower recovery.

4.4 Soil Moisture

SM is an important factor that affects the degree and extent of soil profile disturbance, compressibility of soil, puddling, and rutting (Tergazhi and Peck 1967, Ampoorter at al. 2007), and thus the speed of soil recovery. In this study, increasing values of SM were associated with decreasing values of TP and MP and increasing values of BD and RD at the surface and within the soil profile. SM was affected by traffic intensity and slope gradient, but these effects were not consistent. Our results further showed that SM was not significantly affected by either traffic intensity or slope and were not significantly different from undisturbed areas on either slope class after 16–20 years; SM was thus fully recovered within 20 years.

The partial recovery of physical soil properties on tertiary skid trails on gentle slope gradients may be associated with SM changes in these treatments. According to Froehlich and McNabb (1984), natural soil moisture change is necessary for soil recovery processes because of altered soil temperature regimes, cycles of wetting and drying, and biological activity, which results in alternate swelling and shrinking of soil particles. Severe compaction in the primary skid trails on steep slopes might create a hardpan layer against the water movement into the soil profile, which can lead to moisture saturation above and moisture deficits below depths that may restrict root growth of vegetation. Such changes in soil moisture, combined with little or no aeration exchange in the soil profile also tend to reduce the activity of soil organisms that help cycle nutrients and organic matter. When soils are wet, compaction will increase BD and RD and decrease either TP or MP until only trapped air remains in the soil pores (McNabb et al. 2001), even though the volume of microporosity may be increased in soil profile. Under these conditions, increased trafficking on steep slope results in significant soil disturbance and delayed soil recovery.

4.5 Depth of Rutting

RD increased significantly with increasing traffic intensity and, at least initially, with the skid trail slope gradient, matching findings by others (e.g., Trautner and Arvidsson 2003). The greatest RD of 17 and 21 cm were measured on 1–5-year-old primary skid trails on gentle and steep slopes, respectively. Our results clearly show that RD requires more than 5 years for a full recovery, but that after 20 years RD was no longer measurable on either slope class, at least on tertiary and secondary skid trails. On primary skid trails, RD of 11 and 14 cm remained on gentle and steep slopes, respectively, but even those values represent a significant recovery after 20 years. Our findings are in line with results reported by Dickerson (1976) who estimated that the recovery of wheel-rutted and log-disturbed soil would take 12 and 8 years, respectively.

Tire size is an important factor for reducing the RD of surface soils (Greene and Stuart 1985). In this study, the use of the Timberjack skidder, with its wider tires and lower ground pressure (Table 2) on the sites with a 1–5-year recovery period and the use a the TAF skidder elsewhere may suggest an even faster recovery rate of RD on the most recent skid trails due to lower compaction levels. Unfortunately, due to the lack of soil moisture content data for each skid trail at the time of harvesting, we are unable to compare the initial rutting depths of both types of equipment or relate soil moisture content to initial RD depth. It has been shown, however, that RD and its recovery can be expedited by a low content of soil moisture at the time of the timber harvesting operations as well as high forest floor mass on the surface soil of the skid trail (McNabb et al. 2001, Bygden et al. 2003).

5 Conclusion

This evaluation of effects of timber harvesting operations in a 20-year chronosequence since the last harvest in Iranian mountain forests corroborated findings that link the intensity of skidding traffic and skid trail slope gradient to changes in physical soil properties and soil recovery dynamics. Results indicate that the slope of the skid trail may play a less important role in the initial soil disturbance and subsequent recovery than traffic intensity, however. In general, when compared to untrafficked areas, the physical soil properties tended to partially recover over time toward undisturbed conditions only on tertiary skid trails on gentle slope gradients. While we are unsure whether this result reflects a true recovery or is an artifact of our sampling scheme, we did not find any evidence of a consistent soil recovery in primary and secondary skid trails on any slope and of tertiary skid trails on steep slopes after a 20-year recovery period where the TAF skidder was used. Whereas BD, TP and MP likely require many decades for a full recovery, RD or SM appear to require a much shorter timeframe (i.e., 10 and 20 years, respectively, on secondary and tertiary skid trails and substantial recovery on primary skid trails). Because of the large variability in soil recovery (Fig. 7), it is difficult to draw definitive conclusions about the time required for the full amelioration of compaction effects. We infer from the slow recovery and the rather few and inconsistent statistical differences of soil properties among the different skid trails that most of the soil disturbance is done after the first few passes. We recommend that skidding be concentrated to avoid long-term soil degradation over the entire harvest block, echoing recommendations by others (Wilpert and Schäffer 2006, Zenner et al. 2007). Further research is required in a variety of forest types to collect adequate documentation of the long-term impact of timber harvesting operations on soil hydraulic conductivity and microbial activity on a range of slope gradients and traffic levels to determine the necessary duration for full recovery of physical soil properties.

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