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ORIGINAL PAPER

Influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth

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Abstract The main purpose of this study was to evaluate the effects of skidding operations on the physical and chemical properties of soil as well as root and height growth of maple seedlings. Treatment plots with three replications included combinations of three levels of traffic frequency (three, eight, and 16 passes of a rubber-tired skidder Timberjack 450C) and two levels of trail gradient (≤20 and >20 %) to quantify soil disturbance and corresponding seedling growth. Significant differences between undisturbed areas and machine trail areas of bulk density (0.75 vs. 1.26 g cm^{-3}), total porosity (70.6 vs. 50.4 %), macroporosity (44.5 vs. 18.5 %), microporosity (26.1 vs. 31.8 %), moisture content (50.0 vs. 31.3 %), and forest floor biomass (3498 vs. 1271 kg ha^{-1}) were strongly related to the level of traffic frequency and the trail gradient. Similarly, skidding caused significant reductions in the amount of soil OC (by 41 %), concentrations of nitrogen (53 %), phosphorous (28 %), potassium (31 %), and soil acidity (40 %) compared to undisturbed areas. Finally, germination rate, root length, and stem height of seedlings were inversely related to compaction. Physical and chemical soil properties are often significantly impacted by skidding operations, depending on trail gradient and traffic frequency, which resulted in restrictions to seedling growth.

Keywords Bulk density · Germination · Root length · Soil disturbance · Trail gradient

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Introduction

The compaction of forest soil is a major concern in ground-based timber harvesting operations in the north mountainous forest of Iran. Soil compaction, defined as an increase in soil bulk density that can be caused by rubber-tired skidders and crawler tractors in skidding operations, is one of the most damaging factors, because of the large spatial extent of area affected by machine traffic and the associated duration of adverse effects (Craig 2004; Najafi and Solgi 2010; Ezzati et al. 2012). These machines that weigh 10–20 tons when loaded may seriously influence soil ecosystems as they induce rutting of the upper soil layers and soil compaction (Najafi et al. 2009; Ampoorter et al. 2011).

Soils exposed to machine traffic exhibit reduced soil macroporosity, connectivity of pores, and soil permeability (Berli et al. 2004; Frey et al. 2009; Bejarano et al. 2010; Solgi et al. 2013), while shear strength increases (Williamson and Neilsen 2000; Picchio et al. 2012). The physical effects of soil compaction may thus lead to reductions in water, solutes, and gas movements through the soil, reductions in exchange processes such as changes in carbon dioxide efflux from the soil, and reductions in the availability of water and nutrients (Greacen and Sands 1980; Botta et al. 2007). Reductions in air permeability and soil porosity reduce the penetrability of the soil for roots (Botta et al. 2007) and limit root extension, elongation, branching, density, and penetration of primary roots as well as root access to, and uptake of, soil moisture and nutrients (Greacen and Sands 1980). Effects on root growth can have a significant influence on the performance of seedlings (Finzi and Canham 2000; Kobe 2006). Consequently, soil compaction can compromise seedling establishment and survival (Greacen and Sands 1980; Arocena 2000; Grigal 2000; Yoshida et al. 2005; Kim et al. 2010) and ultimately seedling growth and production (Pregitzer et al. 2002; Zenner et al. 2007; Soto et al. 2015). The severity of seedling growth and production does, however, depend on the soil type and tree species among other factors (Kozlowski 1999; Ampoorter et al. 2011).

A large number of factors influence the extent and severity of soil compaction. These factors can be generally divided in two main groups: machine parameters and operating characteristics (axle load, traction type, traffic frequency, etc.) (Greacen and Sands 1980; Eliasson 2005; Naghdi et al. 2015) as well as climate, site, and soil characteristics (Ampoorter et al. 2007; Naghdi and Solgi 2014). Within machine parameters, the number of machine passes over a forest soil is a factor that significantly influences the degree of soil damage (Ampoorter et al. 2007). Studies showed that most compaction occurs during the first few passes of a vehicle and that subsequent passes have lesser impact, but may increase bulk density and reduce non-capillary porosity to critical levels for tree growth (McNabb et al. 1997). Further, during skidding operations on steep terrain, a given load is subjected to an uneven weight balance on the axles (usually rear axle), which can further increase soil disturbance when a machine experiences considerable wheel slip (Najafi et al. 2010). Consequently, terrain gradient has a strong effect on soil disturbance during mechanized ground-based timber harvesting and causes greater impacts on trails with >20 % gradients compared to the trails with <20 % gradient (Krag et al. 1986; Najafi et al. 2010).

Despite many studies that have investigated the impact of different traffic frequencies and trail gradients on the physical and chemical properties of soils (Greacen and Sands 1980; Ares et al. 2005; Botta et al. 2006; Ampoorter et al. 2007; Jaafari et al. 2014; Naghdi et al. 2016), the effects of traffic frequency and trail gradient on growth and survival of tree seedlings have received little attention. Moreover, most of these studies investigated effects mainly on herbaceous species, and only a few studies considered woody species (Nadezhdina et al. 2006; Alameda and Villar 2009; Ampoorter et al. 2011). To our knowledge, the combined effects of traffic frequency and trail gradient on growth and survival of tree seedlings following skidding operations have not yet received much attention.

Seedling growth and survival following skidding are of particular concern in Hyrcanian oriental beech (*Fagus orientalis* Lipsky) forests that are managed with the selection system. Oriental beech forests cover an area of 245,372 ha or 16.5 % of the total Hyrcanian forest area in Iran, with an estimated 68.7 million m^3 (280 m^3/ha) of standing timber volume, or 30 % of the total timber volume in Iran. Although oriental beech forest sites are highly suitable for timber production, these sites are also located in steep mountainous terrain on marls (35 % lime and 65 % clay) that have low infiltration capacity and are susceptible to intense runoff and erosion after heavy rainfall (Naghdi et al. 2015). Potential erosion is compounded by management approaches where tree felling is done exclusively with chainsaws, and timber is forwarded to roadsides or landings by animal (horses and mules) and heavy machines (rubber-tired skidders, crawler tractors, and modified agricultural tractors or Unimogs) that have been shown to cause soil compaction after few passes over machine operating trails, particularly on steeper gradients (Ezzati et al. 2012; Jaafari et al. 2014; Naghdi et al. 2015). Consequently, when this potential for soil erosion on steep gradients is combined with the high-density machine operating trail network necessitated by selection systems, the natural regeneration success of beech is often suboptimal. For this reason, direct seeding or planting of velvet maple (*Acer velutinum* Boiss) is often done to improve conditions to successfully regenerate oriental beech. Even though velvet maple (*A. velutinum* Boiss) is only a minor component of oriental beech forests that it is a fast-growing species that is considered less susceptible to soil compaction than oriental beech and is widely used in afforestation and forest ecosystem restoration (Sagheb-Talebi et al. 2014). Following the establishment of velvet maple, beech seedlings are then planted after a few years to take advantage of the improved growing conditions created by the maples, which will eventually be extracted after beech seedlings have become established.

The specific objectives of this study were to (i) quantify the influence of different traffic frequencies and trail gradients on the severity of soil surface disturbances, (ii) determine the impacts of ground-based skidding-induced soil disturbances on soil bulk density, total porosity, and forest floor removal, (iii) determine the impact of ground-based skidding and its interaction with trail gradient on soil chemical properties (OC, N, P, K concentrations and soil pH) in the top 10 cm of a forest soil, and (iv) measure and assess the impacts of soil disturbance on germination rate and growth of velvet maple (*A. velutinum* Boiss).

Materials and methods

Site description

This research was conducted from late March 2015 to early October 2015 in the Sorkhekolah forest, Mazandaran province, northern Iran (36°21′N and 36°25′N and 53°5′E and 53°6′E). The harvested stand was a mixed oriental beech (*F. orientalis* Lipsky) and hornbeam (*Carpinus betulus*) forest with a canopy cover of 88 %, stand density of 185 trees/ha, average diameter at breast height of 34 cm, and an average height of 22.3 m. The elevation of the research area is approximately 1520 m above sea level with a northerly aspect and an average annual rainfall of 1300 mm recorded at the closest national weather station. The mean annual temperature is 15 °C, with the lowest values in February. At the time of skidding operations (March 2015), weather conditions had been wet with an average gravimetric soil moisture content of 28 %. Soil texture was analyzed using the Bouyoucos hydrometer method to a depth of 10 cm and was determined to be clay texture with a particle size distribution of 53 % clay (<0.002 mm size), 26 % silt (0.002–0.05 mm), and 21 % sand (0.05–2 mm) along the machine operating trail. The soil had not been driven on before the experiment.

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). Hand felling using chainsaws and axes (especially in thinning operations) is the most common harvesting technique in Iran. The rubber-tired cable skidder was 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 always driven loaded to the maximum load capacity.

Experimental design and data collection

The impacts of skidding operations at different levels of trail gradient and traffic frequency on the soil surface layer (0–10 cm depth) of the machine operating trail were quantified using dry bulk density, total porosity and litter

Table 1 Technical details of the Timberjack 450C rubber-tired cable skidder

Specifications	Timberjack 450C
Empty weight (kg)	10,257
Number of wheels	4
Front tyres	24.5–32
Rear tyres	24.5–32
Average ground pressure (kPa)	221
Engine power (kW)	132
Manufacturing year	1998
Manufacturing location	Canada

Fig. 1 Rubber-tired cable skidder (Timberjack 450C) used for logging operations in a mountain forest of Iran

mass, and compared to undisturbed areas within the same forest stand. In addition, the influence of skidder traffic and trail gradient on the germination rate and stem and root growth of maple seedlings was also assessed. Maple seedlings were chosen because this pioneer species has shade intolerant seeds, is suitable for restoring compacted soils, and is the preferred species for revegetating machine operating trails and landings in Iran (Jamshidi 2005).

A trail was selected for study that encompassed a range of longitudinal gradients without any lateral gradient. With regard to the longitudinal profile and maximum gradient of the machine operating trail, two trail gradient classes were considered (≤20 and >20 %). The gradient ≤20 % contained segments ranging between 4 and 15 %, whereas gradient class >20 % contained segments ranging between 23 and 30 %. Traffic frequencies of the loaded skidder were (i) three passes for light traffic, (ii) eight passes for moderate traffic, and (iii) 16 passes for heavy traffic segments. Therefore, treatment plots included the combination of two levels of trail gradient and three levels of traffic frequency, thus forming six combinations of traffic frequency and trail gradients; each treatment combination was replicated three times, totaling 18 treatment plots.

Treatment plots were 10 m long by 4 m wide and were separated by 5 m (Fig. 2). Treatment plots included three randomly placed 4-m transects across the wheel track perpendicular to the direction of travel with a minimum 2-m buffer zone between transects. 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 transect. Once the forest floor was removed, soil samples with an average weight of 310 g were collected from a depth of 0–10 cm (excluding the recently removed forest floor) at two different locations on each transect: the left wheel track and the right wheel track. Therefore, six soil core samples and six forest floor samples were collected from each of the 18 treatment plots. The soil was cleaned of forest floor material, sampled with a soil hammer and rings (diameter 5 cm, length 10 cm), placed in polyethylene bags, labeled, and transported to the laboratory. At each sampling point, a microplot (1 m wide

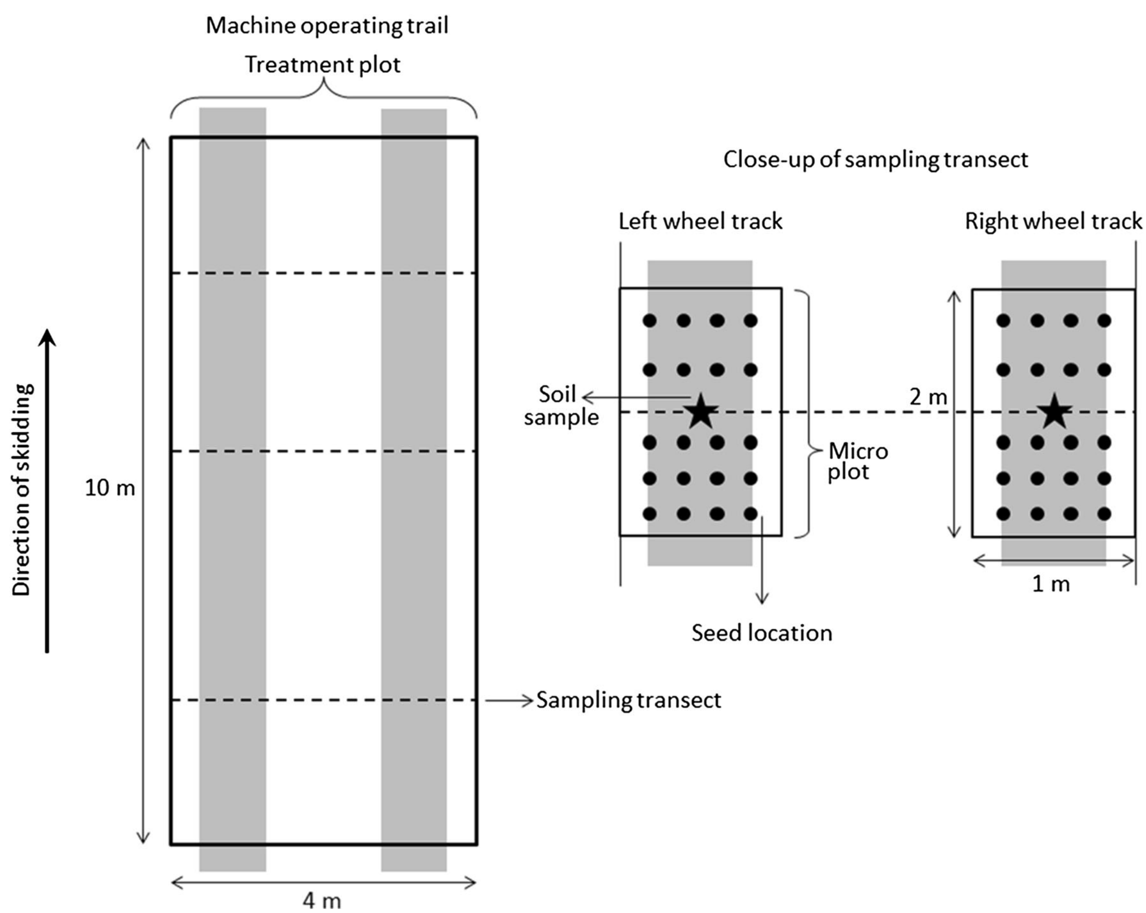

Fig. 2 Schematic of the treatment setup with the location of transects and microplots within the research area. Soil samples are taken from two different locations on each of the three sampling transects

by 2 m long) was established in which 20 points were set up in a grid pattern with a 0.3 m distance between each point. A seed of velvet maple was then placed at each of those 20 points at a depth of 2 cm. Freshly matured seeds were collected during the 2014 growing season from an uneven-aged stand inside the research area. For control purposes, six plots and six microplots (three randomly chosen to be on the one side and three on the other side of the machine operating trail) were also established in the undisturbed area at a distance of 50 m (a distance of at least two tree lengths) from the machine operating trail, where there was no direct skidding impact. The study area was fenced to eliminate deer and boar browsing. All treatments included weed control in the research period after seeding to eliminate the confounding effects that soil compaction can have on vegetation communities and competition pressure (Dyck and Cole 1994).

Laboratory analysis

Soil physical properties

The 108 soil and forest floor samples collected in the field were brought to a laboratory, oven-dried at 105 °C (24 h) and 65 °C (48 h), respectively, and weighted to determine soil bulk density (i.e., the mass of dry soil per unit volume of soil core, g cm^{-3}), soil porosity, and soil moisture content (i.e., the amount of water associated with a given volume or mass of soil).

Total soil porosity was calculated as Eq. (1):

$$AP = 1 - \left(\frac{\rho_d}{2.65}\right) \times 100 \quad (1)$$

where AP is the total porosity (%), ρ_d is the dry bulk density (g cm^{-3}), and 2.65 g cm^{-3} is the particle density measured by a pycnometer on the same soil samples used to determine the bulk density (Picchio et al. 2012).

Microporosity was calculated as Eq. (2):

$$MIP = \theta_m \times \rho_d \quad (2)$$

where MIP is the microporosity (%), ρ_d is the dry bulk density (g cm^{-3}), and θ_m is the water content on a mass basis (%).

Macroporosity was calculated as Eq. (3):

$$MP = AP - MIP \quad (3)$$

where MP is the macroporosity (%), AP is the total porosity (%), and MIP is the microporosity (%).

Soil chemical properties

To determine soil chemical properties, soil samples were air-dried, ground and only particles finer than 2 mm were used for analysis. Due to budgetary constraints, the soil samples that were taken from the two different locations on each of the three sampling transects were combined as were the soil samples taken from the control plots.

Particle size distribution was determined following the Bouyoucos hydrometer method (Kalra and Maynard 1991), while soil acidity was measured using a pH meter with glass electrodes in 1/2.5 distilled water (Jackson 1962). The percentage of OC was determined following the Walkley–Black procedure (Walkley and Black 1934), N was evaluated following the semi-micro-Kjeldahl method (Jackson 1962), P following Bray and Kurtz's (1945) No. 1 method with a spectrophotometer, and K following the ammonium acetate method (Jackson 1962) using a flame photometer.

Seedling survival and growth data collection

All seedlings were assessed for germination, root and stem growth in early October 2015 (180 days after seeding in late March 2015) and the following three response variables were calculated: (1) germination rate; (2) aboveground growth, calculated as the stem length at the end of the study (180 days), and (3) belowground growth, calculated as the root length (the length of main root) at the end of the study.

Statistical analysis

One-way and two-way ANOVAs were used to assess the significance of observed differences in soil physical and chemical properties and seedling parameters under different skidder traffic levels, trail gradients, and their interactions. One-way ANOVA (significance test criterion $\alpha \leq 0.05$) and Tukey's HSD test were used to compare the soil physical and chemical properties and the seedling parameters among the three traffic frequencies (main effects) and to those in undisturbed areas. Spearman's rank correlation coefficients were used to evaluate the strength of the association with compaction on soil physical and chemical properties and to evaluate the strength of the association with soil physical and chemical properties on seedlings growth parameters (germination rate, root length, and stem height). All statistical calculations were performed using SPSS version 11.5.

Results

Soil physical properties

Soil bulk density increased with increasing numbers of skidder passes and increased gradient of the machine operating trail (Table 2). The average bulk density at 0–10 cm soil depth was 0.74 g cm^{-3} in the undisturbed

Table 2 Analysis of variance (*P* values) of the effect of traffic frequency and trail gradient on soil physical and chemical properties and the germination rate, and stem and root growth of maple seedlings

Source of variance	*df*	*P* value*
Dry bulk density		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.108
Total porosity		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	**≤0.005**
Macroporosity		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.182
Microporosity		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	**≤0.005**
Moisture content		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.229
Forest floor		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.174
Organic carbon		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.257
Nitrogen		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	**≤0.005**
Phosphorous		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.318
Potassium		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.539
pH		
No. of passes	2	**≤0.005**
Gradient class	1	0.435
No. of passes × Gradient class	2	0.261
Germination rate		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	0.193
Root growth		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	**≤0.005**
Stem growth		
No. of passes	2	**≤0.005**
Gradient class	1	**≤0.005**
No. of passes × Gradient class	2	**≤0.005**

* *P* values less than 0.05 are shown in bold

area and 1.26 g cm^{-3} in the machine operating trails (Table 3). Heavy traffic on trail gradients over 20 % resulted in the highest dry bulk densities and an increase of 102.7 % compared to undisturbed areas. Heavy traffic on trail gradients ≤20 % resulted in an increase of 82.6 % and dry bulk densities that were similar to those after moderate traffic on steeper gradients. After three passes, bulk density in machine operating trails increased by 31.5 % on gradients ≤20 % and 57.1 % on gradients >20 %.

Total porosity in undisturbed (control) areas ranged between 71.1 and 70.2 % and did not differ significantly between trail gradients. Following skidding operations, total porosity decreased to 60.4–38.4 % and was significantly affected by traffic frequency, trail gradient, and the interaction of traffic frequency × trail gradient (Table 2).

Macroporosity in undisturbed areas ranged between 44.8 and 44.2 % and did not differ significantly between trail gradients. Following skidding, macroporosity decreased to 27.7–9.8 % and was significantly affected by traffic frequency and trail gradient, but the interaction of traffic frequency × trail gradient was not significant (Table 2). Macroporosity decreased consistently with increasing traffic intensity on both trail gradients and with increasing trail gradient at all traffic frequencies. The initial passes decreased macroporosity the most; subsequent passes resulted in relative decreases that were more modest, particularly on steeper trail gradients (Table 3).

Average microporosity in undisturbed areas was 26.1 % and increased significantly with increasing traffic frequency, the gradient of machine operating trail, and the interaction of traffic frequency × the gradient of machine operating trail (Table 2). Microporosity increased consistently with increasing traffic intensity on both trail gradients and with increasing trail gradient at all traffic intensities (Table 3). Heavy traffic on trail gradients over 20 % resulted in the highest microporosity values. Heavy traffic on gradients ≤20 % resulted in microporosity values similar to those after moderate traffic on steeper gradients.

Table 3 Effect of traffic frequency and trail gradient on soil physical properties

Soil physical properties	Gradient (%)							
	≤20 %				>20 %			
	Number of machine passes				Number of machine passes			
	0‡	3	8	16	0‡	3	8	16
Bulk density (g cm^{-3})	0.73^{e} ± 0.08	0.98^{d} ± 0.07	1.19^{c} ± 0.13	1.36^{b} ± 0.11	0.76^{e} ± 0.07	1.17^{c} ± 0.14	1.33^{b} ± 0.09	1.51^{a} ± 0.18
Total porosity (%)	71.06^{a} ± 4.56	60.37^{b} ± 3.75	52.75^{c} ± 2.94	48.02^{d} ± 2.81	70.18^{a} ± 4.06	53.92^{c} ± 3.77	48.61^{d} ± 3.15	38.42^{e} ± 2.63
Macroporosity (%)	44.81^{a} ± 3.12	27.75^{b} ± 1.93	20.63^{c} ± 1.47	15.91^{d} ± 1.64	44.19^{a} ± 2.54	21.04^{c} ± 1.39	16.14^{d} ± 1.22	9.76^{e} ± 0.94
Microporosity (%)	26.25^{a} ± 2.47	32.62^{b} ± 3.19	32.12^{b} ± 3.36	32.11^{b} ± 2.55	25.99^{a} ± 1.83	32.88^{b} ± 2.91	32.47^{b} ± 2.43	28.66^{ab} ± 2.28
Moisture content (%)	50.21^{a} ± 4.40	36.76^{b} ± 3.13	33.55^{c} ± 3.02	28.93^{d} ± 2.16	49.83^{a} ± 3.52	33.07^{c} ± 2.79	30.46^{cd} ± 3.07	24.84^{e} ± 1.97
Forest floor (kg ha^{-1})	3620^{a} ± 273	2287^{b} ± 182	1607^{c} ± 123	824^{d} ± 85	3375^{a} ± 199	1739^{c} ± 116	1022^{d} ± 101	149^{e} ± 73

Different letters indicate statistically significant differences ($\alpha \leq 0.05$) among group means based on Tukey's HSD test

Different superscript letters indicate a statistical difference in soil bulk density among trail gradients at α 0.05

‡ Undisturbed area, no machine traffic

Soil moisture content in undisturbed areas ranged between 50.2 and 49.8 % and did not differ significantly between trail gradients (Table 3). Following skidding traffic, soil moisture content decreased to 36.8–24.8 % and was significantly affected by traffic frequency and trail gradient. Soil moisture content decreased consistently with increasing traffic frequency on all trail gradients and with increasing trail gradient at all traffic frequencies. Heavy traffic on trail gradients >20 % resulted in the lowest soil moisture content.

Mean forest floor biomass per unit area was considerably higher in the undisturbed area (3498 kg ha^{-1}) than in the machine operating trails once traffic passes were completed (1271 kg ha^{-1}) (Table 3). The skidding passes with the loaded rubber-tired skidder caused a significant decrease in forest floor biomass in both trail gradient classes. The forest floor biomass was removed more rapidly on the steeper machine operating trail at each traffic frequency. For example, 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 %. Overall, there were strong significantly negative correlations between soil bulk density and total porosity, macroporosity, soil moisture content, and forest floor mass (Table 4).

Soil chemical properties

Soil samples taken from 0 to 10 cm depth (following the removal of forest floor) showed important differences between the undisturbed area and the machine operating trails with regard to the measured chemical properties of OC, N, P, K, and pH (Table 5). The average OC content in undisturbed areas ranged between 6.5 and 6.3 % and did not differ significantly between trail gradients. Following skidding, the average OC content decreased to 4.9–2.6 % and was significantly affected by traffic frequency and trail gradient, but the interaction of two factors was not significant (Table 2). The relative change in OC content between disturbed and undisturbed plots ranged from −23.6 % with three passes and a gradient ≤20 to −58.4 % with 16 passes and a gradient of >20 %.

The average N content in undisturbed areas ranged between 0.275 and 0.271 % and did not differ significantly between gradients (Table 5). Following skidding, the average N content decreased to 0.223–0.033 % and was significantly affected by traffic frequency and trail gradient, and the interaction of traffic frequency × trail gradient (Table 2).

The reduction in the average P content in the surface soil layer on the machine operating trails ranged from 11.5 % with three passes and a gradient ≤20–44.9 % with 16 passes and a gradient >20 % compared to the

Table 4 Spearman's correlation coefficients between soil physical and chemical properties

Variables	BD	TP	MP	MIP	MC	FF	OC	N	P	K	pH	GR	RL	SH
BD	1.000	−0.995**	−0.984**	0.565	−0.978**	−0.997**	−0.996**	−0.991**	−0.992**	−0.989**	0.993	−0.909**	−0.986**	−0.990**
TP		1.000	0.982**	−0.536	0.977**	0.995**	0.992**	0.987**	0.989**	0.985**	−0.983**	0.904**	0.979**	0.989**
MP			1.000	−0.687	0.998**	0.985**	0.994**	0.954**	0.962**	0.949**	−0.981**	0.837**	0.946**	0.958**
MIP				1.000	−0.692	−0.570	−0.621	−0.462	−0.491	−0.450	0.598	−0.264	−0.457	−0.471
MC					1.000	0.983**	0.992**	0.948**	0.955**	0.940**	−0.972**	0.836**	0.934**	0.948**
FF						1.000	0.997**	0.988**	0.993**	0.983**	−0.991**	0.909**	0.981**	0.988**
OC							1.000	0.979**	0.983**	0.973**	−0.991**	0.887**	0.969**	0.978**
N								1.000	0.992**	0.998**	−0.978**	0.948**	0.993**	0.992**
P									1.000	0.990**	−0.988**	0.924**	0.991**	0.997**
K										1.000	−0.976**	0.94**	0.995**	0.993**
pH											1.000	0.899**	0.981**	0.981**
GR												1.000	0.937**	0.914**
RL													1.000	0.993**
SH														1.000

BD bulk density, *TP* total porosity, *MP* macroporosity, *MOP* microporosity, *MC* moisture content, *FF* forest floor, *OC* organic content, *N* nitrogen, *P* phosphorus, *K* potassium, *pH* hydrogen ions, *GR* germination rate, *RL* root length, *SH* stem height

** Correlation is significant at the 0.01 level

Table 5 Effect of traffic frequency and trail gradient on soil chemical properties

Soil chemical properties	Gradient (%)							
	≤20 %				>20 %			
	Number of machine passes				Number of machine passes			
	0‡	3	8	16	0‡	3	8	16
Organic carbon (%)	$6.52^{a} \pm 0.22$	$4.91^{b} \pm 0.19$	$4.12^{bc} \pm 0.20$	$3.29^{c} \pm 0.15$	$6.33^{a} \pm 0.28$	$4.18^{bc} \pm 0.18$	$3.56^{c} \pm 0.15$	$2.67^{d} \pm 0.13$
Nitrogen (%)	$0.275^{a} \pm 0.012$	$0.223^{b} \pm 0.012$	$0.158^{c} \pm 0.009$	$0.087^{d} \pm 0.007$	$0.271^{a} \pm 0.013$	$0.164^{c} \pm 0.01$	$0.106^{d} \pm 0.01$	$0.033^{e} \pm 0.006$
Phosphorus (ppm)	$43^{a} \pm 3.12$	$36.74^{b} \pm 2.27$	$31.67^{c} \pm 2.36$	$27.41^{d} \pm 1.64$	$40^{a} \pm 2.92$	$32.91^{c} \pm 2.39$	$28.02^{d} \pm 1.71$	$22.88^{e} \pm 1.19$
Potassium (ppm)	$12.53^{a} \pm 0.51$	$11.41^{b} \pm 0.50$	$9.39^{c} \pm 0.44$	$7.71^{d} \pm 0.39$	$12.47^{a} \pm 0.45$	$9.55^{c} \pm 0.43$	$7.84^{d} \pm 0.37$	$6.07^{e} \pm 0.32$
pH (%)	$5.13^{e} \pm 0.29$	$6.29^{d} \pm 0.37$	$7.33^{c} \pm 0.34$	$7.88^{b} \pm 0.42$	$5.47^{e} \pm 0.33$	$6.91^{cd} \pm 0.36$	$7.76^{b} \pm 0.40$	$8.24^{a} \pm 0.40$

Different letters indicate statistically significant differences ($\alpha \leq 0.05$) among group means based on Tukey's HSD test

Different superscript letters indicate a statistical difference in soil bulk density among trail gradients at α 0.05

‡ Undisturbed area, no machine traffic

undisturbed area. Following skidding, the average P content decreased to 36.7–22.9 ppm and was significantly affected by traffic frequency and trail gradient, but not the interaction of two factors (Tables 2, 5).

The average K content was always lower in machine operating trails than the control plots (Table 5). The relative change in K content between trafficked and control plots ranged from −8.7 % with three passes and a gradient of ≤20 to −51.4 % with 16 passes and a gradient of >20 %. Change in mean K content was influenced by the number of passes and trail gradient, but not the interaction between the number of passes and trail gradient (Table 2).

The average soil acidity was significantly influenced by the number of passes, but the effects of trail gradient and of the interaction between number of passes and trail gradient were not significant (Table 2). The average soil acidity in undisturbed areas ranged between 5.1 and 5.5 and did not differ significantly between trail gradients (Table 5). The relative change in soil acidity between trafficked and control plots ranged from 18.7 % with three passes and a gradient of ≤20–55.5 % with 16 passes and a gradient of >20 %. The results showed that there were strong correlations between soil physical and chemical properties. Soil chemical properties (OC, N, P, and K) were negatively correlated with bulk density, but were positively correlated with total porosity, macroporosity, moisture content, and forest floor mass (Table 4).

Survival and growth

The germination rate, assessed at day 180 after seeding, averaged 45.8 % in undisturbed control areas and ranged between 44.6 and 42.8 % after three skidder passes, 38.7–37.1 % after eight skidder passes, and 30.8–28.6 % after 16 passes (Table 6). Germination rates on steeper gradients were 4–8 % lower compared to more gentle gradients. Germination rates were significantly reduced by the number of passes and the trail gradient, but the interaction between these factors was not statistically significant (Table 2). Germination rate was strongly negatively correlated with soil bulk density (Table 4).

Root length of maple seedlings was inversely related to compaction. Root length in soils with a bulk density of 1.5 g cm^{-3} (heavy traffic frequency and gradient over 20 %) was ≤44 % of the maximum length observed in the undisturbed area. The average root length in undisturbed areas ranged between 28.1 and 27.4 cm and did not differ significantly between trail gradients. Root length decreased consistently with increasing traffic frequency on all trail gradients and with increasing trail gradient at all traffic frequencies, with greatest reductions at the highest traffic frequency and steeper gradients (Table 6). Root length on steeper gradients was reduced by a further 14–25 %

Table 6 Effect of traffic frequency and trail gradient on seedling properties

Seedling properties	Gradient (%)							
	≤20 %				>20 %			
	Number of machine passes				Number of machine passes			
	0‡	3	8	16	0‡	3	8	16
Germination rate (%)	$45.25^{a} \pm 5.99$	$44.63^{a} \pm 4.56$	$38.71^{b} \pm 6.28$	$30.83^{c} \pm 6.53$	$46.33^{a} \pm 6.15$	$42.83^{ab} \pm 4.93$	$37.06^{b} \pm 7.12$	$28.61^{c} \pm 5.37$
Root length (cm)	$28.15^{a} \pm 7.23$	$24.76^{b} \pm 6.11$	$19.62^{cd} \pm 4.73$	$16.03^{d} \pm 5.31$	$27.39^{a} \pm 6.37$	$21.48^{c} \pm 4.92$	$15.38^{d} \pm 4.06$	$12.14^{e} \pm 3.94$
Stem height (cm)	$18.74^{a} \pm 4.63$	$15.69^{b} \pm 3.75$	$12.64^{c} \pm 3.22$	$10.56^{d} \pm 2.11$	$17.31^{a} \pm 5.06$	$12.97^{c} \pm 4.13$	$10.17^{d} \pm 2.84$	$7.32^{e} \pm 1.97$

Different letters indicate statistically significant differences ($\alpha \leq 0.05$) among group means based on Tukey's HSD test

Different superscript letters indicate a statistical difference in soil bulk density among trail gradients at α 0.05

‡ Undisturbed area, no machine traffic

compared to gentle gradients. Root length was significantly affected by traffic frequency, trail gradient, as well as the interaction of traffic frequency × trail gradient (Table 2). Root length was strongly positively correlated with soil physical (total porosity, macroporosity, moisture content, and forest floor mass) and chemical properties (OC, N, P, and K), and negatively correlated with soil bulk density and pH (Table 4).

Stem height was significantly lower on seedlings measured on the machine operating trails than in undisturbed areas. Compared to average stem heights of 18 cm in undisturbed areas, the average stem heights were 14.3, 11.4, and 8.9 cm on trails with low, moderate, and heavy traffic frequency, respectively (Table 6). Average stem height decreased consistently with increasing traffic intensity and increasing trail gradient. At all traffic intensities, steeper trail gradients resulted in lower stem height than gentler trail gradients and resulted in further stem height reductions between 18 and 30 % compared to gentle gradients. Stem height was also significantly affected by traffic frequency, trail gradient, as well as the interactions of traffic frequency × trail gradient (Table 2). The results of the correlation analysis indicated that stem height showed a very similar correlation structure to root length, with a strong positive correlation between stem height and root length (Table 4).

Discussion

Although soil compaction is an important stress factor that can affect the development of plants (Kozlowski 1999), limited research has been done from an ecological point of view to link forest soil compaction with tree germination and early growth (Alameda and Villar 2009). This research reports on several novel points: results of the combined effects of traffic frequency and trail gradient on soil physical and chemical properties and results of the effects of light, moderate, and heavy soil compaction on the germination rate and root and stem growth of velvet maple seedlings. Our study has confirmed that skidding increases the dry bulk density and decreases the forest floor biomass, porosity, moisture content, soil OC and concentrations of N, P, K, and hydrogen ions compared to undisturbed areas. More importantly, we also found that the change in physical and chemical properties affected early seedling growth parameters including germination rate, stem and root growth, with potentially longer-term consequences for forest productivity.

After 16 passes on trails with gentle gradients and merely 8 passes on steep trails, dry bulk density values had already increased to 1.36 and 1.51 g cm^{-3}, respectively, and were fast approaching the critical threshold of

1.40–1.55 g cm^{-3} above which plant roots are thought to no longer be able to penetrate soils with fine and medium texture (Kozlowski 1999). These results are in keeping with other studies that have similarly documented more adverse effects of harvesting traffic on soil physical properties on steeper relative to more gentle gradients (e.g., Najafi et al. 2009; Ezzati et al. 2012; Solgi et al. 2014). The much larger effect of machine traffic on soil physical properties on steeper compared to more gentle slopes may be a consequence of the difficulties of skidding in steep terrain. In steep terrain, machines can exhibit severe wheel slip, resulting in more puddling and dragging of the soil (Gayoso and Iroume 1991). Further, when a skidder passes more slowly on a steeper gradient, the top soil is vibrated more and is disturbed more severely compared to flat terrain (Naghdi and Solgi 2014).

An important consequence of increased soil compaction is a change in the pore size distribution toward a decrease in total porosity (Ezzati et al. 2012). The reduction in total porosity after machine trafficking typically occurs at the expense of the large air-filled pores in the soil surface layers due to a conversion of soil macropores to micropores (Williamson and Neilsen 2000). The observed reduction in macropores by 78 % and the increase in micropores by 28 % after 16 passes on gradients >20 % in this study were thus not unexpected. A macroporosity or air-filled porosity threshold of at least 10 % is a prerequisite for sufficient air diffusion, microbial activity, and root proliferation (Brady and Weil 2002; Ampoorter et al. 2007). Our results show that macroporosity decreased to <10 % on steep trail gradients after 16 passes, exposing microbial activity, root and plant growth, and site productivity to serious limitations (Brady and Weil 2002; Ampoorter et al. 2007).

The observed decrease in soil moisture content from 50 % in undisturbed areas to 24.8 % after 16 passes on steep gradients suggests a negative feedback to higher bulk densities, presumably due to compaction. Although this finding has not been universal (see Makineci et al. 2007), soil moisture content has previously been shown to be reduced with increasing traffic intensity and trail gradient, largely due to a decrease in total porosity and macroporosity, and an increase in bulk density at the surface and within the soil profile (Najafi et al. 2009; Ezzati et al. 2012). A reduction in soil moisture with increasing terrain gradient is thought to be associated with more severe soil disturbances that occur on steeper gradients. Soil compaction and forest floor removal reduce the water content of mineral soils, probably as a consequence of less pore space that is available for water infiltration and greater runoff of surface water (Greacen and Sands 1980; Tan et al. 2005).

Apart from bulk density and porosity, another major deficiency caused by the machine operating trails is the loss of organic matter from the forest floor (Najafi et al. 2009). Mixing and/or removal of litter and soil may change the physical, chemical, and biological soil properties. Organic material retention can significantly increase microbial biomass due to increased carbon availability for microbial metabolism (Mendham et al. 2002). The lower mass of the forest floor in the machine operating trails compared to control areas indicates that the forest floor may have been displaced as a result of the skidding activity (Jaafari et al. 2014). In addition, some of the trees along the machine operating trail had been cut and removed during the opening of the trail to ensure easy transportation and skidding of the harvested timbers. The removal of trees would have resulted in a lower tree density along the machine operating trails, which may also explain the decrease in the forest floor biomass compared to the undisturbed area (Demir et al. 2007). Nonetheless, the magnitude of decrease in forest floor biomass after skidding reported here is similar to that found by other researchers (Demir et al. 2007; Makineci et al. 2007; Najafi et al. 2009).

Our study clearly indicates that skidding can have a significant influence on soil chemical properties. The present results and previous reports show that the effects of skidding on the chemical properties of topsoil vary with traffic frequency and machine operating trail gradient (Demir et al. 2007; Jaafari et al. 2014; Naghdi et al. 2016). Decreases in OC and N content following logging operations have also been reported in other studies (Jaafari et al. 2014; Naghdi et al. 2016). Because soil N content in forests generally correlates well with soil organic carbon (Jobbágy and Jackson 2001), skidding can result in large losses of soil N content directly on the machine operating trail (Jaafari et al. 2014). This explains the decrease in OC in this study by approximately 29, 40, and 54 % in low (three passes), medium (eight passes), and high traffic (16 passes) trails, respectively, which compares well with OC decreases of 34, 50, and 64 %, respectively, in low, medium, and high traffic intensity trails documented by Jaafari et al. (2014). The slight differences between these two study results may be associated with differences in the level of litter and topsoil removal in the machine trails, the skidder type used, the soil texture, the soil moisture content during skidding operations, the exact gradient of the machine trails, and the exact number of machine passes (Rab 1996; Naghdi and Solgi 2014). The decreased P and K content in the machine operating trails in this study have also been documented in other studies that reported a decrease in P and K content in machine operating trails with increasing traffic intensity (Naghdi et al. 2016). Finally, the lower soil acidity (pH 7.4) at the 0–10 cm soil depth on the machine trails compared to the undisturbed (control) area (pH 5.3) is consistent with previous findings that have attributed higher pH values in machine operating trails to a host of factors that are directly related to skidding (e.g., removal, mixing, and displacement of the organic layer and topsoil, soil compaction, and exposure of deeper and less acidic soil layers) (Jaafari et al. 2014).

Parallel to the noticeable effects on soil physical and chemical properties from ground-based skidding, soil compaction also significantly decreased seedling growth. The reduction in the average germination rate from 46 % in undisturbed (control) area to 37 % on the machine operating trails supports previous reports of reductions in germination rates due to soil disturbance or compaction (Greacen and Sands 1980; Kozlowski 1999; Jordan et al. 2003). Similar findings by Kozlowski (1999), which show that soil compaction can adversely influence the tree regeneration by inhibiting seed germination and growth of seedlings and by inducing seedling mortality, provide additional evidence that soil compaction can affect the natural regeneration and long-term dynamics of forests (Greacen and Sands 1980).

The reduction in root length to ≤44 % of the maximum length at a bulk density of 1.5 g cm^{-3} following heavy traffic frequency at a trail gradient over 20 % compared to undisturbed areas in this study attests to the added root strength needed to overcome increased soil resistance and penetrate pores of smaller diameters. The increases in soil strength and decreases in macroporosity following soil compaction typically reduce the rate of root elongation and, as a consequence, root length (Greacen and Sands 1980). Similarly, negative effects of soil compaction on root penetration and root length have been related to increases in penetration resistance (Bassett et al. 2005; Bejarano et al. 2005). The steady reduction in root length with increasing bulk density in this study clearly indicates that growth reductions can be observed even before the assumed threshold is reached (Heilman 1981; Singer 1981), which is consistent with previous findings that adverse effects of soil compaction on root growth may change continuously (Powers et al. 1998).

Results of this study further indicate that seedling height growth was significantly reduced by soil compaction on machine trails. This is in line with previously documented adverse effects of soil compaction on stem growth in addition to reductions in root growth (Ferree and Streeter 2004; Bassett et al. 2005; Alameda and Villar 2009). Average tree height reductions between 15 and 59 % in machine trails compared to heights of trees grown in undisturbed areas fall within the range of previously documented findings (Smith and Wass 1980; Thompson 1991). Nonetheless, other studies have found that a moderate soil compaction can increase the contact between roots and the surrounding substrate, allowing for greater water and nutrient absorption (Arvidsson 1999; Gómez et al. 2002a), highlighting the complex relationship of soil compaction and plant growth that can range from beneficial to detrimental (Kozlowski 1999; Souch et al. 2004; Ares et al. 2005; Cubera et al. 2009). Indeed, even for the same tree species *Pinus ponderosa*, the effect of soil compaction on the growth of saplings could be negative, insignificant or positive, depending on the texture or water content of the soil (Gómez et al. 2002b). Similarly, Smith (2003) showed that the effect of soil compaction on tree growth depended on soil texture and soil depth and in a recent meta-analysis, Ampoorter et al. (2011) documented that the effects of soil compaction on growth are often insignificant and vary strongly across soil types and tree species.

Conclusions

In this study, the effects of ground-based skidding performed in the forest were quite comprehensive and ranged from severe impacts on soil physical properties such as increased soil bulk density, reduced total porosity, and reduced forest floor material, to impacts on soil chemical properties such as reduced concentrations of OC, N, P, and K and increased soil pH in the topsoil, to adverse effects on germination rate and growth of velvet maple seedlings. In all cases, increased traffic frequencies on steeper machine operating trail gradients resulted in greater severities of soil disturbances and greater adverse effects on seedlings. Adverse impacts of soil compaction on seedlings could be clearly seen in reductions in the length of the main root of up to 57 % compared to those of seedlings growing in undisturbed soil conditions. This reduction in the size of the root system is a cause for concern because the root system principally determines the proper development of a seedling and ensures its long-term stability. These results suggest that the effects of soil compaction may create particularly challenging conditions for seedling survival during drought periods, because seedlings with short roots may be unable to access water at deeper soil levels. However, even if seedlings are not under the additional stress of potential drought events, reductions in total porosity, soil moisture, and concentrations of macronutrients that typically exceed 40 % at high traffic concentrations on steep gradients have already adversely affected seedlings in the short term, which will likely cause long-term growth reductions of the trees and potentially reductions in productivity at the stand level. Several important consequences can be derived from the effects of traffic frequency and its interaction with terrain gradient for timber harvesting. First, in an operational context dealing with mechanized in-stand wood transportation, machine traffic should be limited to pre-defined machine operating trails to avoid exposing an unnecessary area of soil to the direct contact with a machine. The area designated to machine operating trails should be kept as small as possible to avoid disturbing and compromising the productivity of a large proportion of the forest. Second, harvesting equipment should be used that causes the least amount of adverse effects per pass. Third, comprehensive pre-harvest planning in combination with close monitoring of ongoing operations is key steps in protecting the integrity of forest soils and minimizing the negative effects of machines on the environment. This means that planners need to avoid laying out machine operating trails with gradients >20 % that cause the greatest soil disturbance with the largest adverse effects on seedling performance.

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