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Influence of machine type, traffic intensity, and travel speed on selected soil physical properties during skidding operations

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ABSTRACT

Among the various factors affecting soil compression during wood extraction, travel speed hasn't received much attention. The aims of this study were to (a) assess the effects of two frequently employed wood extraction machines, namely a tractor (Massey Ferguson 285) and a skidder model (Timberjack 450C), equipped with different tire sizes and uneven axle loads with regard to forest soil physical properties and rut formation under various traffic frequencies and travel speeds, and (b) examine the relationship between travel speed and soil bulk density. Treatments included six different traffic frequencies (0, 1, 3, 6, 10 and 15 passes) and three travel speed levels (1, 3 and 5 m s^{-1}) of the two tractors. The number of passes, machine type, and travel speed all show significant effects ($p < 0.05$) on bulk density, total porosity, and rut depth. The skidder exerted statistically significant. Bulk density positively correlated with traffic intensity in all examined levels of travel speed. Porosity in the topsoil (0–10 cm) decreased by an elevating number of passes and this trend was also evidenced as the travel speed decreased. Furthermore, the skidder created, in all cases, deeper ruts than those generated by the tractor. Considering the imminent end of the ban on wood harvesting in the study area in 2016, these insights have practical implications for forest management and wood extraction practices. Forest managers should carefully consider the choice of wood extraction equipment and operational parameters, especially travel speed, to minimize soil compaction and rut formation. The implementation of strategies that support sustainable soil management practices during the wood extraction are paramount to preserving the long-term health and productivity of forest ecosystems.

Keywords: Soil compaction, Porosity, Rut depth, Skidder, Tractor.
Article type: Research Article.

INTRODUCTION

Forest soil compaction during ground-based skidding consists an important deterioration agent by altering the physical and chemical properties of the soil, soil fauna, and plant diversity in the north mountainous forests of Iran (Naghdi *et al.* 2016a,b; Solgi *et al.* 2018; Solgi *et al.* 2020). As the magnitude and duration of damages can be extensive, carefully designed managerial actions are demanded (Ezzati *et al.* 2012; Naghdi *et al.* 2018a). Compaction is the process of rearranging and compacting solid soil particles, resulting in undesirable soil changes such as increased bulk density (Froehlich *et al.* 1981; Najafi *et al.* 2010; Naghdi *et al.* 2015) and reduced total porosity (Rab 1994; Najafi *et al.* 2009; Solgi *et al.* 2016). Water regime is also affected by reductions in soil permeability, infiltration capacity, and water movement (Froehlich *et al.* 1981; Murray & Buttle 2004; Ezzati *et al.* 2012) that may lead to increased surface runoff and erosion (Greacen & Sands 1980; Bagheri *et al.* 2013; Solgi *et al.* 2014). Reduced air permeability and soil porosity limit root penetration of the soil and root expansion, elongation, branching, density, and penetration of primary roots, as well as root access to the uptake of soil moisture and nutrients (Greacen & Sands 1980). These, often combined, root growth effects can have a substantial impact on seedling performance (Kobe 2006). Therefore, seedling establishment and survival, as well as, at a later stage, seedling growth and production, can be harmed by soil compaction (Greacen & Sands 1980; Arocena 2000;

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Grigal 2000; Yoshida *et al.* 2005; Zenner *et al.* 2007; Kim *et al.* 2010; Soto *et al.* 2015). The severity of seedling growth and production, on the other hand, is multifactorial, and depends on a variety of parameters, such as soil type and tree species (Kozlowski 1999; Ampoorter *et al.* 2011). Excessive deformation or rutting of the trafficked region is one of the first evidence that vehicular movement is connected to forest soil disturbance (Najafi *et al.* 2009). In moist or wet soils, ruts are formed as a result of both vertical and horizontal displacement of soil toward the centre or sides of the machine-operating trail. These ruts are closely associated with shearing pressures and soil compression (Horn *et al.* 2004). Following machine trafficking, Davies *et al.* (1973) considered rut depth to be the primary indication of soil compaction. The initial soil attributes (e.g. coarse content, soil texture, soil moisture content, etc.), vehicle specifications (e.g. number of tires, tire width, axle load, and ground pressure), and traffic intensity consist important factors (Botta *et al.* 2006; Solgi *et al.* 2013; Naghdi & Solgi 2014). Due to the complicated interactions between machine features and site conditions during the forest operations, variations in the degree and severity of soil compaction can be evidenced in terms of intensity and distribution. The extent of disturbance caused by logging operations is dependent on a variety of parameters, including the work capacity and environmental efficiency of machine operators (Greacen & Sands 1980; Picchio *et al.* 2012; Solgi *et al.* 2016; Solgi *et al.* 2017; Naghdi *et al.* 2020). Understanding vehicle-soil interactions (Cambi *et al.* 2015) allows for the design of optimized machine operating trail networks that will reduce the negative consequences of ground-based skidding operations (Grigal 2000). Traffic intensity has been found to have a substantial impact on the degree of soil deterioration among machine parameters (Ampoorter *et al.* 2007). According to similar studies, the majority of compaction happens during the first few passes of a vehicle, with subsequent passes having less influence. However, additional passes further increase bulk density and lower non-capillary porosity to, potentially, crucial levels for tree growth (McNabb *et al.* 1997). The severity and spatial extent of compaction in skidding operations can also be influenced by the type of machinery employed (Solgi *et al.* 2016). Naghdi *et al.* (2015) reported smaller increases in bulk density caused by a crawler skidder compared to those caused by two different rubber-tired skidder models over a range of slope gradients. Sheridan (2003), on the other hand, observed no significant differences in soil impact between steel-tracked and rubber-tired skidders, highlighting the hazards of presuming that lower machine static ground pressures will inevitably result in soil impacts of lesser magnitude. Furthermore, the tire inflation pressure has been reported as the most influential tire parameter (Botta *et al.* 2012). Botta *et al.* (2002) and Solgi *et al.* (2016) have associated ground pressure with topsoil compaction, whose increases also lead to more severe soil disturbance (Naghdi & Solgi 2015). The use of wide (flotation) tires exerts results in lower soil density increases (Botta *et al.* 2012). Finally, the machine travel speed has also been reported as a factor determining the impact of vehicle traffic on the soil (Jamshidi *et al.* 2013). However, compared to other components of machine traffic, the impacts of skidder travel speed on soil disturbance have received less attention. A primary concern of forest managers is the minimization of adverse and often long-lasting impacts of vehicular passes, especially when ground-based skidding is applied (Rab 2004). Determining the extent of disturbance caused by different travel speeds of operating skidders is critical in this direction, especially in developing countries, where the purchase of more modern and sophisticated equipment is not possible due to financial constraints (Koutsianitis & Tsioras 2017). The purpose of this study was to analyse how skidding operations conducted with examined machine types, one tractor, and one skidder impact the physical properties of forest soil and contribute to the formation of ruts. More specifically, the study examines the following hypotheses:

Hypothesis 1. There is a significant effect of skidding operations on forest topsoil compaction (0-10 cm) as exerted by the machine type, under various traffic frequencies, and travel speeds. Hypothesis 2. There is a significant relationship between the travel speed of the machine type and soil deformation, with variations observed at different levels of traffic intensity. This study aims to provide a comprehensive understanding of the impact of skidding operations on forest soil physical properties and rut formation. By exploring the effects of different tractor machine types, traffic frequencies, and travel speeds, we seek to contribute valuable insights to the field of forest management and soil conservation.

MATERIALS AND METHODS

Site description

The study was carried out in August 2019 in the Tanian forest, Guilan Province, Northern Iran (37°26'N, 49°13'E). The study area was located in low altitude (120 m above sea level) and on sloped terrain that has been afforested, mostly, with poplar and alder. The study area's soil classification, based on the World Reference Base (WRB), falls within the Cambisols category. The soil texture along the examined machine operating trails was clay-loam and it was determined using the Bouyoucos hydrometer method (Kalra & Maynard 1991). The soil size distribution of the machine operating trails (The length was 800 m and the slope less than 10%) is presented in Table 1. The average depth of soil to the bedrock was 70 cm. Generally, these areas are at high risk of erosion due the combination of steep mountainous conditions, heavy precipitation, and marl and limey sediments. Marl's constitution of 35% lime and 65% clay results in low infiltration capacities and high susceptibility to intense run-off and erosion. The average annual rainfall was 990 mm according to the closest national weather station, located 20 km away. The maximum and minimum mean monthly rainfalls of 149 mm and 44 mm have been measured in October and August, respectively. The mean annual temperature of the study area is 16 °C, with February being the coldest month of the year. The weather conditions were dry and warm during the data collection period (Booklet of revised forestry plan, 2013). The trail used for the skidder measurements had an average soil moisture content of 20% in contrast to the trail designated for agricultural tractor measurements, which had a slightly higher average soil moisture content of 23%. In both cases, the soil had not been driven on before.

Table 1. Soil particle size distributions at a depth of 0–10 cm for the machine operating trails. The range of particle size was < 0.002, 0.0021–0.05 and 0.051–2 mm for clay, silt, and sand, respectively. Soil texture in all trails was clay loam.

Sample trails	Soil particle size distributions (g 100 g^{-1})		
	Clay	Silt	Sand
Machine operating trail (MOT) 1	29	39	32
MOT 2	35	37	22
MOT 3	31	40	29
MOT 4	27	39	34
MOT 5	30	38	32
MOT 6	29	37	34

Forest operations and machine specifications

Tree-felling and processing at the study site were carried out motor-manually by chainsaws, whereas axes were used in thinning operations. The machines used in the skidding operations were a rubber-tired cable skidder (Timberjack 450C) and an agricultural tractor (Massey Ferguson 285; Fig. 1), hereafter referred to as skidder and tractor, respectively, whose main technical specifications are presented in Table 2. No further pieces of equipment (e.g. extra tracks or chains) were attached on the pneumatic tires of the two machines.

Table 2. Technical specifications of the examined machines.

	Machine model	
	2WD Massey Ferguson 285 (tractor)	4WD Timberjack 450C (skidder)
Engine power (kW)	62	132
Front tires	750–18	24.5–32
Rear tires	18.4–30	24.5–32
Total weight (kg)	3114	11450
Front weight (kg)	1420	6540
Rear weight (kg)	1694	4910
Soil contact area (m^2) for a single tire (front)	0.0484	0.1277
Soil contact area (m^2) for a single tire (rear)	0.1771	0.1151
Ground pressure front tire (kPa)	143.9	251.1
Ground pressure rear tire (kPa)	46.9	209.2

Experimental design and data collection

We tried to examine the impacts of different ground pressures, as exerted by the two tractor types on the soil surface layer (0–10 cm depth). Various combinations of machine passes numbers and travel speeds were tested across six machine-operating trails to assess soil dry bulk density, total porosity and rut depth, with the objective to compare the results from trafficked areas to those of undisturbed soil. All trails had a low longitudinal gradient (<5%) and no lateral gradient. Treatment plots were designated to examine the combination of (i) two, commonly used in skidding operations in Iran, rubber-tired tractors, (ii) six levels of machine passes (0, 1, 3, 6, 10, and 15 passes) and (iii) three travel speed levels (1, 3 and 5 m s^{-1}). Each machine was driven unloaded on an individual trail. The experimental choice of using unloaded machines, instead of attaching an average load to them was purposeful, in order to examine this baseline scenario. This experimental setup will be expanded to include loaded machines in a future comprehensive evaluation. Public truck scales were used to determine the individual and total axle loads of each machine prior to data collection. The tire/soil contact area was measured using the methodology described in Solgi *et al.* (2016). The average static ground pressure for each machine axle was calculated as the total axle load divided by the tire-soil contact area for both tires (Botta *et al.* 2009).

Fig. 1. Photos of the examined machines: (a) rubber-tired skidder Timberjack 450C, (b) agricultural tractor Massey Ferguson 285.

A total of 36 combinations examined (2 machine types × 6 levels of machine passes × 3 levels of travel speed), which were randomly replicated three times resulting in 108 designated plots, with an area of 40 m^2 (10 m long and 4 m wide) each (Naghdi *et al.* 2020). To prevent interactions among neighboring plots, 5–m long buffer zones were implemented between them. Within each plot, five line transects were drawn perpendicular to the skidder's direction of travel, spaced 2 m apart from each other. Along each transect two soil samples were collected from the depth of 0–10 cm, one from the left wheel track (LWT), and one from the right one (RWT; Fig. 2). Soil sampling was carried out by a soil hammer and cores. The cores had an internal diameter of 5 cm and a length of 10 cm, resulting in a weight of 325 g. Samples were then placed in polyethylene bags, sealed, labeled, and transported to the laboratory, where they were promptly weighed to obtain their wet mass. The samples were oven dried at 103 ± 2 °C and their moisture content was determined gravimetrically after drying (Kalra & Maynard 1991).

Soil bulk density was determined according to Equation (1):

$$D_b = W_d / VC \qquad \textbf{(1)}$$

where D_b is the dry bulk density (g cm^{-3}),

W_d is the weight of the dry soil (g), and

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

Total soil porosity was determined according to Equation (2):

$$AP = (1 – D_b / 2.65) \qquad \textbf{(2)}$$

where AP is the total porosity (%),

D_b is the dry bulk density (g cm^{-3}), and

2.65 (g cm^{-3}) is the particle density.

Ruts that surpassed (i) 2 cm in depth from the top of the mineral soil surface; and (ii) 2 m in length were sampled, following the method described by Najafi *et al.* (2009). According to this method, a specially formed 1 m long iron bar is used, featuring 40 rods spaced at 25 mm intervals along it. Rut depth was calculated as the average depth of 40 rod readings on the iron bar within the ruts that met the sampling criteria (Fig. 3).

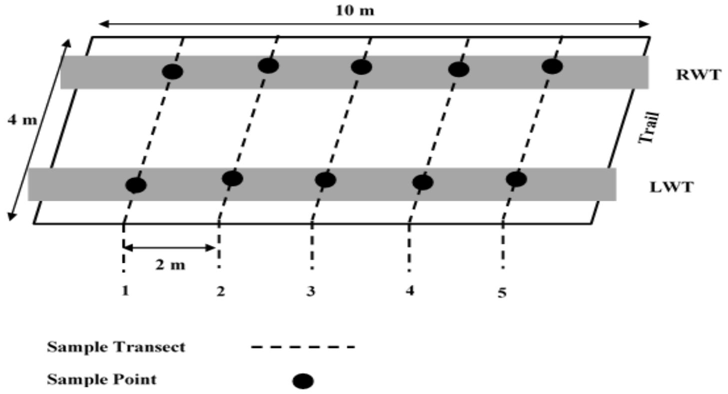

Fig. 2. Schematic of the sampling method used in each study plot.

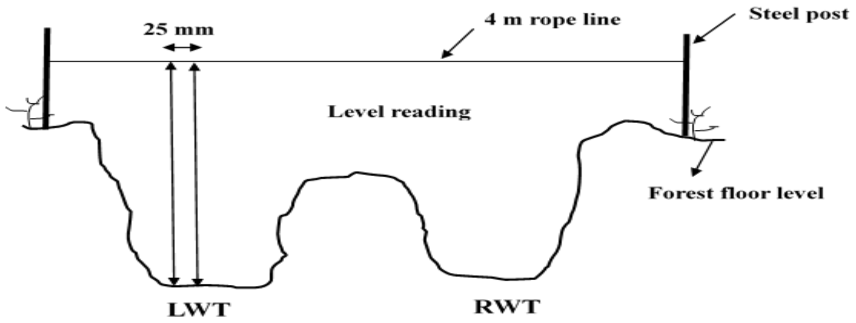

Fig. 3. Graphical presentation of the rut depth measurement method.

Statistical Analysis

One-way and three-way Analysis of Variance were used to identify significant differences with regard to average bulk density, total porosity and rut depth among the various factor combinations and to assess the significance of interaction effects. Tukey's HSD post-hoc test was used to determine the significance of differences between average bulk densities, total porosities and rut depths for the different traffic level and travel speed treatments (Zar 1999). Paired t-tests were used to analyze soil properties data for the two ground pressure levels. Statistical calculations were performed using SPSS version 11.5 and for all tests, the significance level was set to $\alpha = 0.05$.

RESULTS

Soil type and moisture content

The soil particle size distributions of the six adjacent machine-operating trails were found to be similar and belonged to the clay loam soil type (Table 1). Due to the dry and warm conditions during the data collection and the average soil moisture content within the range of 20 – 23%, it was decided to omit soil moisture from further analysis in the present study.

Soil dry bulk density

Dry bulk density in undisturbed areas ranged from 0.66 to 0.71 g cm^{-3} (Table 3), but machine traffic increased it to the range of 0.83 – 1.56 g cm^{-3}. Dry bulk density was significantly affected by machine ground pressure, traffic frequency and travel speed, as well as by the interactions of traffic frequency × ground pressure, and traffic frequency × travel speed (Table 4). The average soil bulk density on the skidder trail increased with machine passes, ranging from 0.89 g cm^{-3} (after one pass) to 1.56 g cm^{-3} (after 15 passes). This was also valid for the tractor trail, however, the bulk density values were lower, ranging from 0.83 g cm^{-3} (after one pass) to 1.49 g cm^{-3} (after 10 passes; Table 3). For both forest machines, dry bulk density increased by elevating traffic intensity at all travel speed levels (Table 3) and with decreasing travel speed at all traffic intensities (Table 3). The results showed that a travel speed rise from 1 to 5 m s^{-1}, decreased the soil bulk density on the skidder trails by about 11% and on the agricultural tractor trails by 8%.

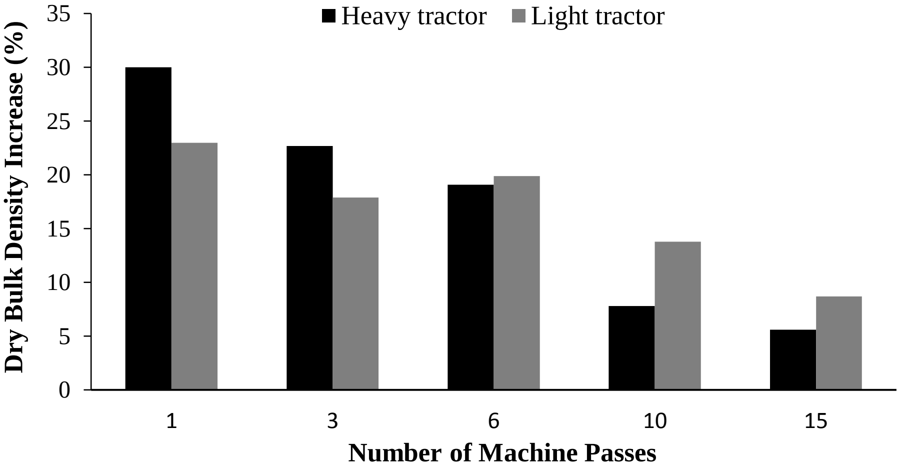

Fig. 4. Relative increases of soil dry bulk density compared to the previous number of machine passes.

The initial first pass resulted in the highest increase of dry bulk density (by at least 23 and 30% compared to the undisturbed soil, for the tractor and skidder, respectively); subsequent passes resulted in further, more limited relative increases (8% and 6% after 15 passes for the light and heavy model, respectively; Fig. 4). Data analysis showed that the skidder, the heavier machine, increased soil bulk density more than the tractor (Fig. 5). This might indicate that the decisive role of ground pressure as a soil compaction factor during forest operations. Furthermore, there is evidence of a strong positive relationship between the travel speed of the machine and soil bulk density that is supported by the linear regression models with very high predictive powers ($R^2 > 0.90$), for both machine types.

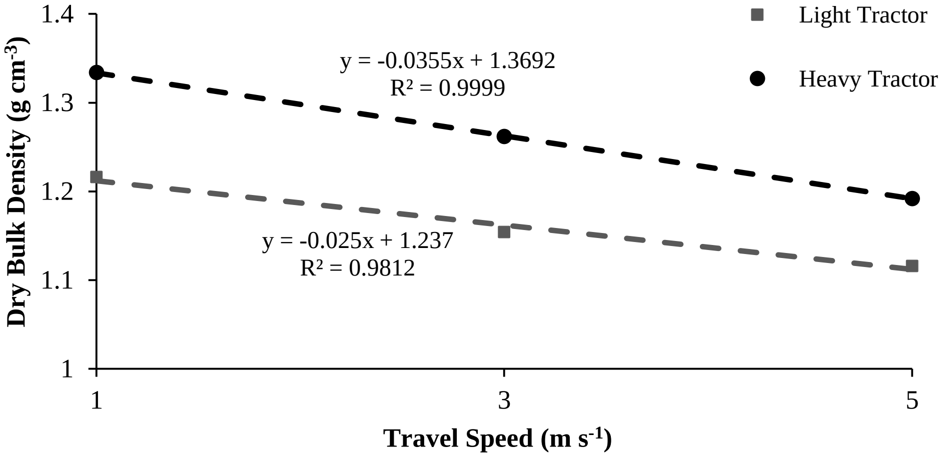

Fig. 5. Effect of travel speed and tractor type on soil bulk density.

Total porosity

Total porosity in undisturbed areas ranged between 71.9% and 72.6% and did not differ significantly among the trails (Table 5), nevertheless, machine traffic reduced it to the range of 42.3 – 67.5%. Total porosity was significantly affected by ground pressure, travel speed, traffic frequency, the interaction of ground pressure × travel speed, and the interaction of all three factors (Table 4). Traffic of the light agricultural tractor caused mean. Reductions in total soil porosity of 6.7%, 15.4%, 23.6%, 31.2% and 36.2% following 1, 3, 6, 10 and 15 passes, respectively. The reductions in total soil porosity following skidder's traffic were higher, i.e., 12.0%, 20.3%, 29.8%, 34.8% and 38.9% after 1, 3, 6, 10 and 15 passes, respectively. In both tractor types, total porosity decreased consistently by dropping travel speed at all traffic intensities (Table 5). Low travel speed resulted in the lowest total porosities in both cases (Fig. 6).

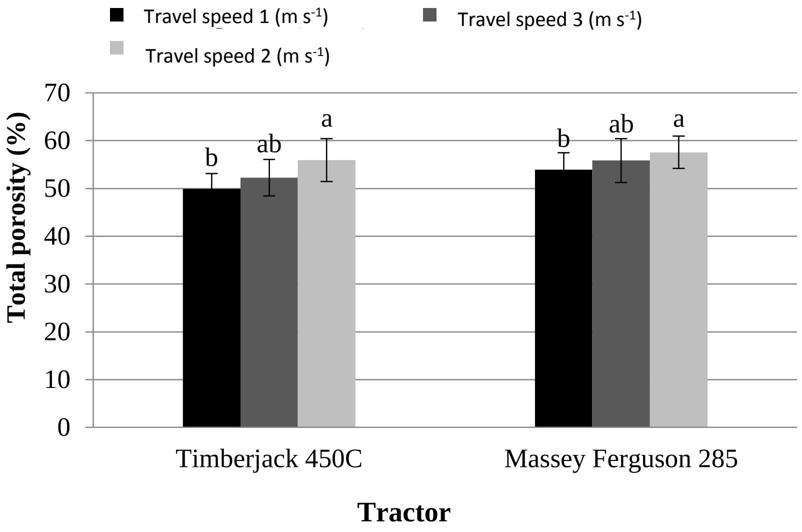

Fig. 6. Effect of the travel speed and tractor type on soil porosity.

Rutting

Following machine traffic, rut depth ranged from 2.2 to 43.2 cm (Table 6) and it was significantly affected by machine ground pressure, traffic frequency, travel speed, the interaction of traffic frequency × travel speed, and the interaction of all three factors (Table 4). Ground pressure did not exert a significant effect on rut depth after one machine pass, however, this changed when traffic increased to three passes. Three passes could be perceived as a threshold value, above which rut depth values almost doubled in the skidder treatments compared to those found in the tractor treatments. Regardless of the tractor type, rut depth increased invariably with i) increasing traffic intensity at all examined travel speed levels (Table 4) and ii) decreasing travel speed at all traffic intensities (Table 4). Finally, low travel speed resulted in the highest rut depths for both tractor types (Fig. 7).

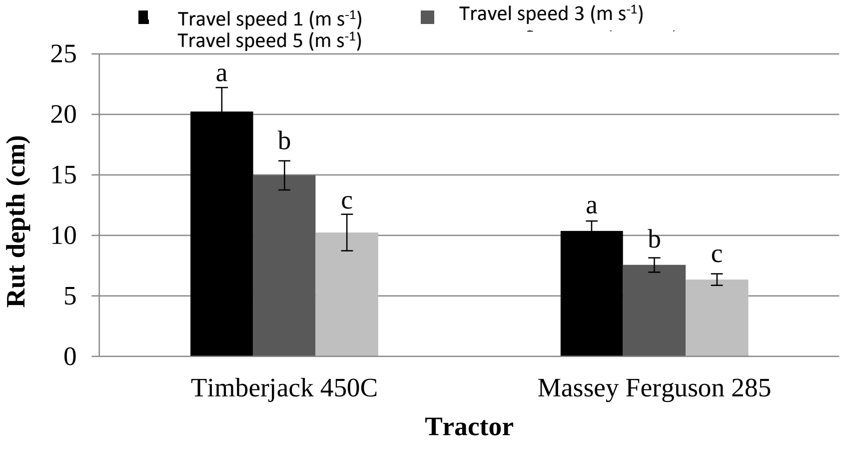

Fig. 7. Effect of the travel speed and tractor type on rut depth.

Table 3. Effect of the number of machine passes and travel speed on soil bulk density (g cm^{-3}). Different letters indicate statistically significant differences ($\alpha < 0.05$) among group means based on Tukey's HSD test.

	Machine type											
Travel speed (m s^{-1})	**4WD Timberjack 450C**						**2WD Massey Ferguson 285**					
	Un	**1**	**3**	**6**	**10**	**15**	**Un**	**1**	**3**	**6**	**10**	**15**
1	$0.70^{Ae}\pm0.05$	$0.94^{Ad}\pm0.08$	$1.17^{Ac}\pm0.09$	$1.46^{Ab}\pm0.12$	$1.52^{Aa}\pm0.13$	$1.56^{Aa}\pm0.14$	$0.69^{Ae}\pm0.05$	$0.85^{Ad}\pm0.07$	$1.05^{Ac}\pm0.08$	$1.26^{Ab}\pm0.12$	$1.42^{Aa}\pm0.12$	$1.49^{Aa}\pm0.12$
3	$0.71^{Ae}\pm0.05$	$0.90^{Ad}\pm0.07$	$1.13^{ABc}\pm0.10$	$1.32^{Bb}\pm0.11$	$1.45^{Ba}\pm0.11$	$1.51^{ABa}\pm0.12$	$0.66^{Af}\pm0.07$	$0.83^{Ae}\pm0.09$	$0.98^{ABd}\pm0.09$	$1.17^{ABc}\pm0.08$	$1.34^{ABb}\pm0.13$	$1.45^{Aa}\pm0.10$
5	$0.69^{Af}\pm0.04$	$0.89^{Ae}\pm0.07$	$1.05^{Bd}\pm0.09$	$1.21^{Cc}\pm0.09$	$1.33^{Cb}\pm0.11$	$1.47^{Ba}\pm0.13$	$0.69^{Af}\pm0.06$	$0.83^{Ae}\pm0.07$	$0.93^{Bd}\pm0.09$	$1.12^{Bc}\pm0.10$	$1.28^{Bb}\pm0.09$	$1.45^{Aa}\pm0.13$

Note: Different letters indicate statistically significant differences ($p < 0.05$) among group means based on Tukey's HSD test; Capital letters highlight statistically significant differences among travel speed classes (column); Lower case letters refer to the comparison made among six classes of traffic intensity on each machine type and travel speed class (row).

Table 4. Analysis of variance (*p* values) of the effects of machine passes, ground pressure and travel speed on soil physical properties.

	***p*-values**		
Source of variable	Bulk density	Total porosity	Rut depth
Passes	≤ 0.05	≤ 0.05	≤ 0.05
Ground pressure	≤ 0.05	≤ 0.05	≤ 0.05
Travel Speed	≤ 0.05	≤ 0.05	≤ 0.05
Passes × Ground pressure	≤ 0.05	0.613	0.127
Passes × Travel speed	≤ 0.05	0.446	≤ 0.05
Ground pressure × Travel speed	0.725	≤ 0.05	0.118
Passes × Ground pressure × Travel speed	0.329	≤ 0.05	≤ 0.05

p-values less than 0.05 are given in bold.

Table 5. Effect of the number of machine passes on total porosity (%). Different letters indicate statistically significant differences (α ≤ 0.05) among group means based on Tukey's HSD test.

Travel speed (m s^{-1})	Machine type											
	4WD Timberjack 450C						**2WD Massey Ferguson 285**					
	Un	**1**	**3**	**6**	**10**	**15**	**Un**	**1**	**3**	**6**	**10**	**15**
1	72.1^{Aa} ±4.3	62.7^{Ab} ±4.9	54.7^{Ac} ±3.8	46.2^{Ad} ±3.7	43.8^{Ae} ±3.9	42.3^{Ae} ±2.8	72.1^{Aa} ±5.1	66.9^{Ab} ±4.5	58.7^{Ac} ±3.9	52.3^{Ad} ±3.4	46.5^{Ae} ±3.4	45.2^{Ae} ±2.7
3	72.6^{Aa} ±4.5	63.9^{Ab} ±5.1	57.1^{ABc} ±3.5	50.6^{Bd} ±3.8	45.8^{Be} ±3.6	43.9^{Ae}±3.1	71.9^{Aa} ±4.7	67.6^{Ab} ±4.8	60.8^{ABc} ±4.1	55.4^{ABd} ±3.9	49.8^{ABe} ±3.7	45.7^{Af} ±2.8
5	72.5^{Aa} ±4.6	64.4^{Ab} ±4.8	61.2^{Bc} ±3.9	55.6^{Cd} ±4.2	52.1^{Ce} ±3.8	46.5^{Bf} ±2.9	72.3^{Aa} ±5.2	67.5^{Ab} ±4.6	63.6^{Bc} ±3.7	57.3^{Bd} ±3.9	52.4^{Be} ±4.0	47.1^{Af} ±3.1

Note: Different letters indicate statistically significant differences ($p < 0.05$) among group means based on Tukey's HSD test; Capital letters highlight statistically significant differences among travel speed classes (column); Lower case letters refer to the comparison made among six classes of traffic intensity on each machine type and travel speed class (row).

Table 6. Effect of the number of machine passes on rut depth (cm). Different letters indicate statistically significant differences (α ≤ 0.05) among group means based on Tukey's HSD test.

Travel speed (m s^{-1})	Machine type											
	4WD Timberjack 450C						**2WD Massey Ferguson 285**					
	Un	**1**	**3**	**6**	**10**	**15**	**Un**	**1**	**3**	**6**	**10**	**15**
1	0^{Ae}	0^{Ae}	3.6^{Ad} ± 0.28	21.8^{Ac} ± 1.35	32.5^{Ab} ± 2.47	43.2^{Aa} ± 3.45	0^{Ae}	0^{Ae}	2.2^{Ad} ± 0.17	10.1^{Ac} ± 0.87	15.9^{Ab} ±1.19	23.7^{Aa} ±1.83
3	0^{Ae}	0^{Ae}	3.1^{Ad} ± 0.24	15.4^{Bc} ± 1.08	23.7^{Bb} ± 1.85	32.6^{Ba} ± 2.88	0^{Ad}	0^{Ad}	0^{Bd}	7.3^{Bc} ± 0.59	12.4^{Bb} ±0.93	18.1^{Ba} ±1.42
5	0^{Ad}	0^{Ad}	0^{Bd}	9.7^{Cc} ± 0.76	16.2^{Cb} ± 1.29	25.3^{Ca} ± 2.16	0^{Ad}	0^{Ad}	0^{Bd}	6.5^{Cc} ± 0.43	10.7^{Cb} ±0.74	14.6^{Ca} ±1.17

Note: Different letters indicate statistically significant differences ($p < 0.05$) among group means based on Tukey's HSD test; Capital letters highlight statistically significant differences among travel speed classes (column); Lower case letters refer to the comparison made among six classes of traffic intensity on each machine type and travel speed class (row).

DISCUSSION

A precise prediction of soil disturbances is not possible due to the multifactorial nature of the topic. The effects of soil type, terrain, skidding equipment, machine specifications, machine operation (e.g. travel speed), weather conditions during the skidding, and the capacity of the machine operators on soil disturbances (e.g. Najafi *et al.* 2009; Naghdi & Solgi 2014; Solgi *et al.* 2016; Naghdi *et al.* 2020) have been the topic of previous research, compared to the effects of ground pressure and travel speed of operating machinery, which have received considerably less attention. The results showed a positive association between dry bulk density and traffic frequency (Table 3). This aligns with Najafi *et al.* (2009) who examined soil compaction resulting from four levels of traffic frequency (3, 7, 14 and 20 passes) of the rubber skidder HSM 904 across three levels of slope (gentle <10%, moderate 10–20%, steep >20%). Similarly, Solgi *et al.* (2020) observed a comparable relationship in their study involving three skidder types, two trail gradient levels (<20% and >20%), and four traffic frequency levels (4, 8, 15, and 40 passes). According to our findings, the pattern of increase differentiated between the two machine types with the skidder exerting, by far, the greatest impact on the soil during its first few passes. Sadeghi *et al.* (2022) reached the same conclusion in a previous study that was also conducted in Tanian forest, Northern Iran. In their study, these authors reported that the soil bulk density increased by 35% and 43% after a single pass of the Timberjack 450C on soil water contents of 18% and 31%, respectively. Moreover, bulk density further increased by 25% and 20% after two additional machine passes. The heavier Timberjack 450C exerted more than four times higher ground pressure underneath the rear axle than the agricultural tractor (209.2 kPa vs 46.9 kPa), which also resulted in greater soil bulk densities. Our finding is in line with Solgi *et al.* (2016), who reported a strong positive relationship between ground pressure and compaction effects observed during machine traffic. Nevertheless, the association between heavier machinery and increased compaction is not inherently straightforward. In a similar study by Solgi *et al.* (2023), carried out in Shaft forest, Guilan Province, Iran, the impacts of two types of skidders on soil physical properties were compared. The examined machines were the cable skidders TAF E655 and Timberjack 450C, having a mass of 6,800 kg and 10,275 kg, respectively. Despite having a lower weight, TAF E655 exerted higher ground pressure under the axles (348 kPa) than the Timberjack 450C (221 kPa) because of its narrower tires, which has a smaller contact area and the wheel load is acting on a small area, thereby increasing pressure on the soil. The results of this study indicate that the selection of machine type had a significant impact on soil physical properties, suggesting the need for machine modifications to mitigate soil disturbance (Labelle *et al.* 2022). Soil compaction was also affected by the travel speed of the examined vehicles. An increase of the skidder speed from 1 to 5 m s^{-1} decreased the soil bulk density by about 12%, whereas the respective decrease in the case of the tractor was about 8%. A similar trend was reported by Sadeghi *et al.* (2022) after examining combinations of five traffic frequencies (1, 3, 7, 10, and 15 passes) of Timberjack 450C, at three levels of travel speed (1, 3, and 5 m s^{-1}) and two levels of soil water content (18% and 31%). Regardless of traffic frequency and water content, reducing travel speed led to significantly higher dry bulk density and more pronounced decreases in soil porosity compared to higher travel speeds. Additionally, increased soil water content resulted in deeper ruts across all combinations of traffic intensity and travel speed. According to Jamshidi *et al.* (2013), this finding might be due to the decreased contact duration between the tractor wheels and the soil surface at higher travelling speeds. Total porosity on the machine operating trails was found considerably lower than the total porosity of the undisturbed soil. Similar to bulk density, there is a notable positive correlation observed between machine type–specifically, the combination of its weight and equipment – and soil porosity. The traffic frequency levels exerted a considerable impact, as one machine pass decreased total porosity by 6.7% and 12.1% in the cases of the light and skidder, respectively (Table 5). Sadeghi *et al.* (2022) determined that the impact of skidding with Timberjack 450C at a speed of 1 m s^{-1} compared to 5 m s^{-1} on soil porosity was equivalent to elevating traffic frequency by one category, irrespective of soil water content. To illustrate, total porosity values after intense traffic (15 passes) at 5 m s^{-1} resembled those following moderate traffic (7 passes) at 1 m s^{-1}. Similarly, moderate traffic (7 passes) at 5 m s^{-1} yielded total porosity values similar to those after light traffic (3 passes) at 1 m s^{-1}. In both examined machine types, total porosity dropped by decreasing travel speed. Lower total porosity values as those found on machine operating trails may further worsen soil aeration and the resultant respiration processes of microorganisms (Horn *et al.* 2004; Solgi *et al.* 2016). Mean rut depth increased by elevating ground pressure, rising traffic frequency and decreasing travel speed of machine. The correlation between rut depth and traffic frequency observed in this study has been previously documented in diverse ecosystems (Botta *et al.* 2006; Eliasson & Wästerlund 2007; Najafi *et al.* 2009; Solgi *et al.* 2018). The fact that the first pass of both machine types did not induce rutting in this study may be attributed to the relatively low soil moisture content range (20% - 23%) during the data collection period. Generally, soil moisture content during forest operations has been positively associated with rut depth (McCurdy *et al.* 2004; Naghdi & Solgi 2014). The higher values of rut depth after 3, 6, 10 and 15 skidder passes (range 3.6 cm – 43.2 cm) compared to those of the tractor (range 2.2 cm – 23.7 cm) may be attributed to the higher ground pressure exerted on the soil. These values are comparable to those reported by Solgi *et al.* (2016) in a study where up to 10 machine passes of the same machine types examined in the present study were compared. Najafi *et al.* (2008) reported rut depths of 18 cm after 14 passes of the rubber skidder HSM 904 on a slope < 10%, that increased to 27.5 cm and 34.5 cm, when slope increased to 10–20% and >20%, respectively. Solgi *et al.* (2022) reported a rut depth of 23.8 cm after 15 passes of Timberjack 450C at a speed of 1 m s^{-1} on a similar water content to that of the present study (18%). However, our highest value of 43.2 cm has exceeded by 81% the value reported by Solgi *et al.* (2022) for the same experimental conditions. On the contrary, this is a lower value than that of 57.8 cm reported by Solgi *et al.* (2022) when the moisture content increased to 31%. Botta *et al.* (2002, 2006) has reached a similar conclusion, stressing the direct relationship between topsoil disturbance and the exerted ground pressure. In a later study, Botta *et al.* (2009) reported that a light tractor causes deeper ruts than a heavier one. This result was attributed to its the smaller tire and, evidently, the smaller soil contact area that resulted in higher ground pressure. Finally, in our study, machine passes at slower travel speeds were associated with more severe ruts compared to that with faster travel speeds due to higher contact duration between soil surface and tractor wheel, a result also reported by Jamshidi *et al.* (2013).

CONCLUSION

This study was carried out with the objective of examining the combined effects of two wood extraction machine types, at different levels of machine traffic and travel speed on selected soil properties. The results demonstrate that all examined factors exert considerable soil disturbance. Within the limits of the experimental conditions, forest managers and executives should consider the following points:

Attention should be given to heavier machines exerting higher ground pressure. In cases of sensitive areas, the use of lighter machines equipped with wider tires should be prioritized. Low travel speeds during wood extraction should be avoided, when possible. The adverse effects of low travel speed and high traffic frequency can be mitigated by careful planning of forest operations and, when necessary, redesigning the forest road network. As an intermediate step, a map of the trail network where problematic areas will be defined would be very helpful to machine operators, facilitating a more eco-efficient wood extraction. Furthermore, limiting the movement of harvesting and extraction machines only to the predefined machine-operating trails can also help to reduce ground disturbance. This is crucial since research confirms that the highest level of disturbance occurs within the first machine passes.

Disclosure statement

No potential conflict of interest was reported by the authors.

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