Effects of Forwarder Operation on Soil Physical Characteristics: a Case Study in the Italian Alps

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Abstract

One of the most important issues in ground based wood extraction in forestry is to minimize the soil damage caused by heavy forestry machines. Generally, harvesting effects include changes in vegetation nutrient availability, soil microclimate/structure and litter quantity/quality. Several studies were carried out on the impacts of heavy machines on the soil. However, only few studies took into consideration the effect of bogie tracks on the soil. The research focuses on the influence of forwarder machines equipped with bogie tracks on the soil compaction through changes of physical soil parameters and precisely bulk density, porosity, shear and penetration resistance. The study was carried out in a conifer stand of Larix decidua *Mill. and* Picea abies *L. in a forest of North-eastern Italy during logging with forwarder. In this site, 3 tracks were identified, 2 concerned loaded forwarder passages and 1 control (no passages). The tracks were: (i) track A with a slope of 31% with 2 passages and track B with a slope of 3% having 10 passages. Soil samples were collected on all tracks in order to determine the influence of forwarder passes on soil physical properties. The results showed a different impact of logging operations on the soil of different tracks.*

Keywords: forwarder, bogie track, soil compaction

1. Introduction

One of the most important issues of the forest sector is to minimize the ground damage caused by heavy forestry machines during forest operations (Edlund et al. 2013). Generally, harvesting effects include changes in vegetation, nutrient availability, soil microclimate and structure and litter quantity and quality (Keenan and Kimmins 1993, Jurgensen et al. 1997). However, adequately managed forest ecosystems are suggested to be highly resilient in the long-term perspective (Sanchez et al. 2006). Forest operations, such as forwarding and skidding, have a high potential for soil compaction (Jamshidi et al. 2008, Cambi et al. 2015, 2016). Harvesting induced soil compaction depends on several factors (Berli et al. 2004, Arthur et al. 2013, Berli et al. 2004, Han et al. 2006, Magagnotti et al. 2012, Sakai et al. 2008) and among them one of the most important is the means of propulsion (Alakukku et al. 2003, Cambi et al. 2016, Eliasson 2005, Marchi et al. 2014, Picchio et al. 2011, Picchio et al. 2012a, 2012b). The means of propulsion influence the size of the contact area that changes continuously due to accelerating/braking. Superimposition of different types of stress from neighbouring contact areas (e.g., tandem tires, pendulum axles, bogies) may occur, leading to stress paths specific for any axle or wheel arrangement (Alakukku et al. 2003, Savelli et al. 2010). Due to their lower contact area, wheeled vehicles generally disturb soil more dramatically than tracked ones (Johnson et al. 1991, Jansson and Johansson 1998). Bogie tracks, in spite of increasing the mass on the trailer by 10–12%, may reduce rut depth by up to 40% when compared to rather wide and soft tires, which is probably due to a reduction in the relative rolling resistance coefficient (Bygdén et al. 2004). In addition, bogies of forestry vehicles are used to increase the traction and stability of the machine and to increase the ride comfort of the operator (Meyer et al. 1977, Mac Donald 1999, Pijuan et al. 2012, Alakukku et al. 2003, Bygdén and Wästerlund 2007). The use of bogie tracks may reduce both the depth of the ruts and the soil compaction (i. e. Ansorge and Godwin 2007, Sakay et al. 2008, Syunev et al. 2009, Gerasimov and Katarov 2010, Uusitalo et al. 2011).

Rut formation in the soil is a sign that the load is higher than the bearing capacity in the upper soil layer (Bygdén et al. 2004). Some energy applied to tracks to deform the soil (Yong et al. 1984), thus reducing the rut formation, would generally mean reducing rolling resistance energy (Muro 1982). This means a smaller risk of negative effects on forest growth (Bygdén et al. 2004). A key point to be made here is that the resulting rolling resistance, as the coefficient obtained, is the towing force required to move the device divided by the vertical load (Wong 1989 and Okello et al. 1994). The benefits relative to the use of bogie tracks established from these studies are:

⇒ reduction in relative rolling resistance coefficient
⇒ reduction of rutting
⇒ reduction of surface cone resistance in ruts of about 10%

Recently, Gerasimov and Katarov (2010) have investigated the influence of a bogie track on soil compaction. Edlund et al. (2013) considered a new design of tracked bogie called the long-tracked-bogie (LTB) to combine the features of wheels and tracks in a single bogie design; the LTB showed about 3 and 4% higher pull force at 75 and 90% slip, respectively, than the conventional bogie. In addition to the results shown, LTB appears to pass wider ditches/cavities, more smoothly with a lower pitch angle, than a conventional bogie (Edlund et al. 2013).

The aim of our research was to investigate the influence of a bogie track on physical soil parameters through soil compaction, as well as the impact of slope terrain and forwarder traffic. Soil compaction was evaluated by analyzing the changes in bulk density, porosity, shear and penetration resistance.

2. Methods and data

2.1 Site description and soil sampling

Experiments were carried out in the Dolomite area of the Northern-east Alps in Italy close to Borca di Cadore (46°26'14''28 N; 12°13'14''16 E). The climate of this area is alpine and the mean annual precipitation in the last five years is 1150 mm. The mean annual temperature in the same period was 8°C with the minimum temperatures below 0°C in the coldest months and maximum temperatures over 30°C in the warmest months.

The study site is an even-aged conifer stand of *Larix decidua* (Mill. 1768) and *Picea abies* (L.) H. Karst and located between 1550 and 1600 m a.s.l. The area was selected because it is a focus point due to the presence of Italian and foreign logging companies that use this type of forest machines. The tests were conducted in June 2014. In this area 3 trails (of 18 m in length) were identified – 2 affected by passes and 1 control (no passes). The trails were:

⇒ trail *A* with the slope of 31% and affected by 2 passes
⇒ trail *B* with the slope of 3% of and affected by 10 passes

Table 1 shows in details slope percentages of trails.

The soil in the test area was clay and the moisture was 19% during the test. Each of the identified trails (Fig. 1) were divided into three plots (approximately

Table 1 Slope percentage

	Plot	Length	Longitudinal slope	Lateral slope
Unit		m	%	%
Trail *A*	1	6	–30	5
	2	6	–31	
	3	6	–32	
Trail *B*	1	6	–2	0
	2	6	1	
	3	6	2	
Control	1	6	15	1
	2	6	18	
	3	6	14	

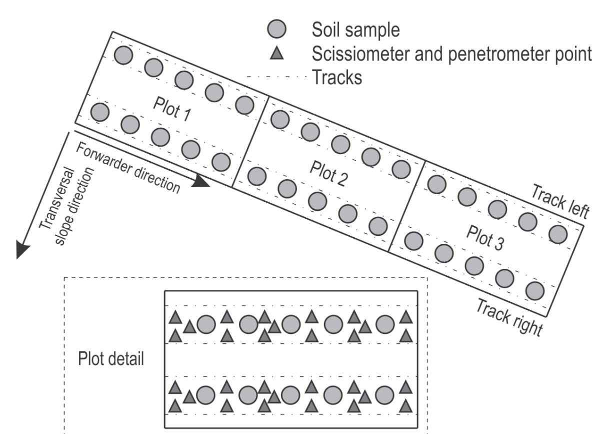

Fig. 1 Sample scheme of a trail

6.30 m), where 30 soil samples were sampled (15 within the left track and 15 within the right track) for a total of 90 soil samples of tracks (30 soil samples x 3 plots). Soil samples were collected by a rigid metallic cylinder (8.5 cm high and 5.0 cm inner diameter) after litter removal. Considering all tracks, bulk density and porosity values were calculated for 90 soil samples to analyze the soil compaction.

The samples were placed in plastic bins and transported to the laboratory, where the BD and soil porosity (n) were determined for each soil sample collected by the following formulas:

$$\text{Bulk density} = \text{Dry}\ \frac{\text{Weight}}{\text{Volume}}\ \text{of cylinder } (158.96\ \text{cm}^3) \quad (1)$$

$$n = \left[\frac{D_p - D_b}{D_p}\right] \times 100 \quad (2)$$

Where:

D_p is the particle density measured by a pycnometer on the same soil samples used to determine the bulk density

Close to each sampling point, penetration resistance and shear resistance were measured in triplicate using a TONS/FT2 penetrometer and a GEONOR 72412 scissometer, respectively. These samples were made of 30 measures per track (10 measures x 3 plots). Statistical analyses of data were done using STATISTICA 7.1 Software. All data were checked for normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene test) and then MANOVA analysis and factorial ANOVA were applied to check differences between treatments. Post-hoc testing was conducted with Tukey HSD test method.

2.2 Description of forest vehicle used

The forwarder used in this study was a John Deere JD1110 D of 17.5 tons (displacement 4140 cm^3 and 121 kW). The forwarder was equipped with 8 wheels Nokian Forest Rider 700/50x26.5 tires inflated to 550 kPa and passed over the trail in one direction at the average speed of 4 km/h. The ground pressure data were: 47 kPa for front empty and loaded and 32 kPa for rear empty and 90 kPa for rear loaded. Descriptions of machinery are shown in Table 2. Table 3 shows the estimated traction data for the forwarder used according to Wästerlund (1992).

Table 2 Description of the forwarder used

Dimensions of forwarder 1110D – 8 wheel		Value	Unit
A	Length	10,310	mm
B	Width	2880	mm
C	Transport Height	3700	mm
D	Ground Clearance	605	mm
E	Wheelbase	5400	mm
F	Load Stake Width	2760	mm
G	Length of Wood Bunk	4580	mm
H	Approach Angle	39	°

3. Results

The control bulk density value was 0.83 g cm^{-3}; the post-treatment bulk density increased slightly upwards to 0.87 g cm^{-3} in trail *A* and to 0.91 g cm^{-3} in trail *B*. The control porosity value instead was 68.8% and post-passes decreased to 67.2% in trail *A* and to 65.5% in trail *B*. Regarding resistance forces of the soil (i) the shear resistance value increased from 24.02 to 43.62 kPa in trail *A* and to 38.65 kPa in trail *B*. Also (ii) the penetration resistance value increased from 1.84 to 2.25 MPa in trail *A* and to 3.72 in trail *B*. The percentage variations for all parameters are shown in Table 4.

Table 3 Estimated traction data for the forwarder used

Type	Unit	Forwarder 1110D			
		Front empty	Front loaded	Rear empty	Rear loaded
Mass	kg	10,500	10,483.4	7000	13,896.6
Wheels	n	8	8	8	8
Real mean ground pressure	kPa	47	47	32	90
Contact area	cm^2	26,058	26,058	26,058	26,058
1/3 of contact area	cm^2	17,372	8,686	8,686	8,686
Max. ground pressure	kPa	75.2	75.2	51.2	144

Table 4 Percentage variations of physical parameters

Trail	Passages	Bulk density	Porosity	Shear resistance	Penetration resistance	Litter + duff layer
Unit	n	g cm^{-3}	%	kPa	MPa	cm
Control	0	0.83	68.8	24.02	1.84	3.5
A	2	+5%	–3%	+82%	+22%	–29%
B	10	+10%	–4%	+19%	+102%	–43%

Table 5 MANOVA analysis (Wilks value: 0.0312; *df*: 6, 530; *p*-value <0.001) for the four variables tested in three treatments. For the HSD results, different letters show difference between treatments

		Shear resistance				Penetration resistance				Bulk density				Porosity			
		Mean	Std. dev.	Std. err.	HSD	Mean	Std. dev.	Std. err.	HSD	Mean	Std. dev.	Std. err.	HSD	Mean	Std. dev.	Std. err.	HSD
Unit	N	kPa	kPa	kPa		MPa	MPa	MPa		g cm^{-3}	g cm^{-3}	g cm^{-3}		%	%	%	
Total	270	35.430	8.900	0.542		2.603	0.916	0.056		0.870	0.202	0.012		67.2	7.6	0.5	
Diff. stat		**				**				*				*			
Trail *A*	90	43.617	4.235	0.446	a	2.250	0.454	0.048	a	0.869	0.215	0.023	a, b	67.2	8.1	0.9	a, b
Trail *B*	90	38.650	2.494	0.263	b	3.722	0.506	0.053	b	0.914	0.251	0.027	b	65.5	9.5	1.0	b
Control	90	24.022	2.323	0.245	c	1.837	0.298	0.031	c	0.826	0.096	0.010	a, c	68.8	3.6	0.4	a, c

The results of MANOVA analysis, made for comparing the two trails and the control, show a significant statistical difference between all the variables tested (Tab. 5). In particular, regarding the analysis of the first 8.5 cm of soil, a significant statistical difference in bulk density and porosity was recorded between the control and trail *B*, while for the trail *A* the high SD value does not permit to consider the average value statistically different from both the control and the trail *B*. Focusing the analysis on the first 4 cm of soil, the shear and penetration resistance data highlighted a significant impact in both paths compared to the control It can be shown and highlighted how these parameters behave after the forwarder passes on the slope. In fact, the greater slope (trail *A*) was more influential on shear resistance and the minor slope (trail *B*) was influential on penetration resistance.

A specific factorial ANOVA was applied to compare the two trafficked trails checking differences between the two forwarder tracks (right or left side). The results showed a statistical difference between the two trails only for shear and penetration resistance, while a different situation was revealed for the two tracks (Tab. 6). In the trail *A*, the low number of passes showed a statistically significant impact only for the shear and penetration resistance, with clear differences between the tracks due to the trail transversal slope. In the trail *B*, the highest number of passes showed a statistically significant impact for all the variables studied, with low statistical differences between tracks.

4. Discussion and conclusions

In the last decade, several studies have evaluated the effects of bogie tracks on forest sites (Bygdén et al. 2003, Sakay et al. 2008, Gerasimov and Katarov 2010),

Table 6 Factorial ANOVA analysis (Wilks value: 0,646; *df*: 3, 174; *p*-value <0.001) for the four variables tested in two treatments. The underlined values show statistically significant differences between the two tires. R= right; L= left

Trail	Shear resistance		Penetration resistance		Bulk density		Porosity	
	kPa		MPa		g cm^{-3}		%	
Track	R	L	R	L	R	L	R	L
A	46.8	40.4	2.4	2.1	0.89	0.85	66	68
B	38.9	38.4	3.5	3.9	0.85	0.98	68	63

making comparison with wheel treatment, and the last study also considered a new design of tracked bogie (Edlund ed al. 2013). This paper has given an overview of the possible effects on the ground that can occur in the alpine environment, following timber extraction by a forwarder equipped with bogie tracks, considering two trail slopes, several passages and the differences between the two tracks due to transversal slope. These two aspects have not yet been analyzed for bogie track until now.

The results obtained show a clear difference in soil physical parameters before and after trafficking. In particular, the four soil properties monitored in this research (bulk density, porosity, shear and penetration resistance) were suitable for assessing the impact of bogie tracks on the physical quality of soil. In trial *A* – with greater slope and minor forwarder passages – bulk density, porosity and penetration resistance did not change significantly, while shear resistance increased substantially. In trail *B* – with lower slope and major number of forwarder passages – all soil properties underwent significant changes, suggesting much higher deterioration of soil. With the increasing number of passes, the compacted zone deepened and partly collapsed, and there was a lateral bulging of the soil, as also verified by Gerasimov and Katarov (2010). On the trail with lower slope, the high value of the vertical force component was more stressed in the soil and this considerably affected the penetration resistance. With the increase of the slope, the resultant force (sum of the vertical and horizontal components) had a major effect on the shear resistance.

The results of this study help to increase the knowledge about the impact of a high level of mechanization on forest soil. Other studies have been made on this topic with medium to large forwarders (20 – 38 t) used for wood transport (Jacobsen and Greacen 1985, Jansson and Johansson 1998, Eliasson 2005). These results can also concur for better assessing when different levels of mechanization can apply. In effect, as also found in other studies (Picchio et al. 2012, Marchi et al. 2014) that compared medium and high level of mechanization, high level of mechanization affected bulk density and porosity with similar percentages. It should be noted that, speaking of these specific variables, only the number of passes greatly affects the soil proprieties. The differences or rather the innovative aspects highlighted by the results of this study concern both parameters – penetration and shear resistance. The percentage values of impact found differ from those reported in the cited references and strictly connected to trail slope and number of passes. However, this was a preliminary investigation because only one forest site was analyzed. In addition, there is no much information on any study of this topic for the Italian Alps. So, it is not possible to determine clearly the level and use of mechanization. The topic requires further studies on the effects of soil compaction due to bogie tracks. In particular, it would be interesting to have more trails to compare them with trails of the same slope and number of forwarder steps.

Further research should focus on investigations:

⇒ to assess the effect on physical variations over time (in terms of fertility and soil degradation)

⇒ to evaluate the variations in term of soil microbial components after the forwarder passage

Further information and data on these aspects could give a better overall picture of the impact on the environment.

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