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# Evaluation of soil compaction caused by passages of farm tractor in a forest in southern Italy

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**Abstract.** In recent decades, the use of heavy machinery in forest management has significantly increased, causing the compaction, that often remains for many years and may contribute to a decline in long-term site productivity. Severity of the damage depends on vehicle mass, weight of the carried loads, ground morphology, and soil properties, such as moisture. In Southern Italy, timber extraction is mainly done by farm tractors and the study was carried out in a conifer stand to evaluate the changes in penetration resistance, the water content, the bulk density and the porosity, after different numbers passes 0 (control), 1, 5, 10 and 15 respectively, of one farm tractor (Landini – Landpower 135 TDI). The results indicated that all parameters were significantly higher in the trafficked soil portions rather than in the undisturbed ones. We can conclude that a significant relationship was observed between compaction degree and traffic intensity. In fact, the passage of forestry machines causes soil compaction, leading to significant changes in the soil structure and moisture conditions.

**Key words:** Forest Soil, Tractor Farm, Extraction, Machine traffic, Compaction.

## INTRODUCTION

Soil plays a crucial role in forest ecosystems by mediating the nutrient, water and energy flows that maintain forest productivity and sustain biodiversity (Dominati et al., 2010). Soil, however, is highly sensitive to improper forest management practices, and to large-scale logging activities in particular. Soil compaction reduces the pore space volume, especially that of the intercrumb pore space (macropores), thereby altering the habitat of soil organisms both directly (Van Der Linden et al., 1989; Kaiser et al.,1991) and indirectly by changing the physical properties of soil. Furthermore, soil compaction entails lower water infiltration and hydraulic conductivity, which contribute to more water logging on flat terrain, and more runoff and erosion on slopes (Jansson & Johansson, 1998; Grace et al., 2006).

Logging is perceived as one of the major causes of damage to forest vegetation (Alexander, 2012). Generally, the effects of timber harvesting include changes in vegetation, nutrient availability, soil microclimate and structure, and litter quantity and quality (Keenan & Kimmins 1993; Jurgensen et al., 1997; Proto et al., 2016a). For this region it is important minimize any damage to the ground that is likely caused by heavy machine use during forest operations (Edlund et al., 2013). When harvesting timber, the extent of soil compaction that occurs will depend on various site factors, which are not limited to just the characteristics of soil (e.g. its texture) (Ampoorter et al., 2007). Along with soil moisture and organic matter (Greacen & Sands, 1980; Rohand et al., 2003), one must also consider the frequency of machine passes (Wang et al., 2007), the harvesting system (Froehlich et al., 1985), and the type of machine and its characteristics (Krag et al., 1986; Nugent et al., 2003), mass of the vehicles and their loads (Susnjar et al., 2006), including those types that are 5–40 Mg and number of wheels and their tire inflation pressure (Eliasson, 2005) as well as the amount residual logging slash (Eliasson & Wasterlund, 2007).

The current trend in forestry is to increase the size, power, and load of the logging machines, which can weigh from 12 to 16 Mg in an unloaded state (Ampoorter et al., 2007). Much, if not all, of the soil compaction during timber harvesting will occur during the first 10 passes of a vehicle, but the impact is concentrated in first three passes (Froehlich et al., 1985). These initial passes cause the greatest soil compaction relative to subsequent passes; nevertheless, the latter may further disturb the soil by deepening the ruts. Ruts form through the vertical and horizontal displacement of soil, to either the middle or to the sides of the skid trail, and they are associated with shearing stresses and soil compression in moist or wet soil (Horn et al., 2007). Subsequent vehicle passes generally have little additional impact (Ampoorter et al., 2007; Bolding et al., 2009), but soil bulk density can still increase significantly after more than three passes (Gayoso & Iroume, 1991).

This experimental study was performed in Calabria, in southern Italy. In this region, the forest area has expanded by 40.6% (nationwide, forests have expanded by 34.7%), and its average annual increase in wood volume exceeds, and occasionally doubles, the estimated increase seen in other Italian production forests (Proto & Zimbalatti, 2015). In Calabria, the most common method to harvest trees is referred to as 'traditional', because it exemplifies an early stage of mechanization (Zimbalatti, 2005). This method relies primarily on agricultural tractors, which are sometimes equipped with specific forest-related machinery (e.g., winches, hydraulic cranes, log grapples), and uses animals for gathering and yarding purposes (Macrì et al., 2016). Unfortunately, the current level of mechanization is fairly low (Zimbalatti & Proto, 2009). In Southern Italy, as in many regions of the world, farm tractors serve as a multipurpose vehicle with many applications, particularly in forestry activities. For example, such modified farm tractors may be used to skid the logs from stumps to the landings, to transport the logs in 'tractor-trailer', and to load and unload the logging trucks (Ozturk & Akay, 2007). This low-level of mechanization to extract forest resources is driven by the features of the forest sites, the characteristics of the forest properties, and the small dimensions of many of the forest enterprises (Negri et al., 2016). Within this context, this study aimed to evaluate the impact on soil from a farm tractor (Landpower 135 TDI) as a function of its traffic intensity. Specifically, we were interested in the changes in penetration resistance, water content, and bulk density and porosity of soil that resulted after five different number of passes: 0 (i.e., control), 1, 5, 10, and 15, respectively. The overall objective is to provide useful scientific and technical information, such as the threshold levels of machine traffic intensity, for the development of best management practices for forestry operations in southern Italy with a view to soil preservation and, by extension, enhancing forest productivity and ecosystem functionality.

## MATERIALS AND METHODS

### Site description

The study was conducted in September 2016 in the Massif Serre Vibonesi region. The forest here is located at 587406 E – 4235438N (WGS_84 – Fuso 33). Elevation is approximately 1080 m above sea level, with a northern aspect. Average annual rainfall in this area amounts to 1,000 mm, with the lowest monthly average precipitation occurring in July (20 mm) and the highest in December (150 mm). Mean annual temperature is 12.8°C, with the lowest values in January. The soils in this area developed from igneous and metamorphic rocks and are classified as Umbrisols, with an udic soil regime moisture. The forest here is dominated by Silver fir (*Abies alba)* trees and it covers 33 ha with a slope of 0%–30%. Canopy cover is estimated at 90%, the average tree stem diameter is 46 cm, average tree height is 25.7 m, and the stand density is 580 trees $ha^{-1}$.

The machine used in this study is the Landini 135–Landpower TDI, which is powered by a 6-L Perkins 1106-E60TA turbo diesel six-cylinder engine (Fig. 1). The rear tires were larger than the front tires in width and in diameter and the air pressure of all the tires was fixed was fixe at 15 psi. The main technical features of the tractor are shown in Table 1.

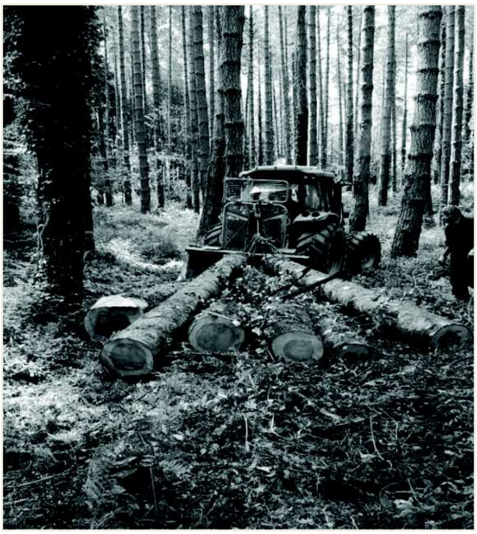

**Figure 1.** Machine used in the experiments.

**Table 1.** Technical characteristic Landini 135 – Landpower

| Parameters | Unit | Value |
|---|---|---|
| Power | kW | 98.4 |
| Weight | Mg | 5,787 |
| Wheelbase | Cm | 279 |
| Length | Cm | 514 |
| Width | Cm | 220 |
| Height | Cm | 276 |
| Front tires | - | 420/70 R 20 |
| Rear tires | - | 520/70 R 38 |

All logs (of various dimensions) were extracted from the stump area to the roadside landing by using a ground-based extraction system. The study forest area has a reliable main road network that is flanked by a provincial road; the trails that were opened during tree felling were then used as the secondary road network (Cavalli & Grigolato, 2010).

Soil texture along the trails was determined to be sandy loam (following analysis that used the Bouyoucos hydrometer method) (Kalra et al., 1991).

**Experimental design and data collection**

A skid trail 3.5-m wide and 280-m long, with upslope skidding direction, was selected for the experiments. The longitudinal profile showed that the slope of the skid trail ranged from 2% to 20%. In this study, the impact of skidding on the surface soil layer (0–10 cm depth) of the skid trail were examined by quantifying the penetration resistance, water content, bulk density and the porosity as a function of traffic intensity, and comparing these results with the respective values of samples taken from an undisturbed area. Buffer zones of at least 5 m in length were created between plots to avoid confounding interactions. Our experimental design had four levels of traffic intensity: 1, 5, 10, and 15 passes; each level was replicated five times for a total of 20 plots. Each plot was 10-m long and 3.5-m wide and divided into four equal parts (Fig. 2). In total 450 samples were collected: 100 for each level of traffic and 50 for the areas undisturbed. Furthermore, in these plots we also measured the rut depth made by the passes; however as the ground was not completely flat, this could have been slightly mall overestimated where in those spots of uneven ground. During the harvesting operation and data collection, values of soil moisture content were relatively stable, ranging from 28% to 31% at a 10-cm soil depth.


**Figure 2.** Sample scheme of a trail.

The soil samples were collected using a rigid metallic cylinder (250 $cm^3$) after first removing any litter on the soil surface. When extracting the steel cylinder from the soil, care was taken to minimize disturbance to the soil content, which were put into a plastic bag and transported to the laboratory. There, the samples were weighed and oven-dried to determine their water content and bulk density. The water content (WC) was determined according to the ‘Official Methods of Chemical Soil Analysis’ (G.U., 13/09/1999). In this method, the soil moisture content is determined and expressed as a percentage of its oven-dried (constant) weight. Soil bulk density (*Db*) is calculated by the following equation (Naghdi & Solgi, 2014) and expressed in units of g $cm^{-3}$ (1):

$$Db = \frac{Wd}{VC} \tag{1}$$

where $Wd$ = weight of the dry soil, and $Vc$ = volume of the soil cores (250 $cm^3$).

Porosity ($P$) is a value that expresses the relative amount of pore space in the soil sample. It is not measured directly, but instead calculated from using the derived bulk density and the particle density (Brady & Weil, 1996; Tanveera et al., 2016) by the following equation:

$$P = 1 - \frac{Db}{dp}\ 100 \tag{2}$$

where $Db$ = bulk density, and dp = particle density; this value was 2.65 g $cm^{-3}$.

To measure penetration resistance as a proxy for soil compaction, we used a portable penetrometer (SC900 Soil, Compaction Meter, Field Scout) that had a 1/2" diameter cone tip. The penetrometer was manually pressed into the soil to a depth of 10 cm to measure the penetration resistance data which it directly stores.

**Statistical Analisys**

Separate one-way ANOVA in SPSS software v.20 tested for any significant differences in average bulk density, total porosity, penetration resistance, and moisture among the five traffic levels (including control). For a given soil response variable, the Tukey multiple range test was used to see which level means differed significantly ($p < 0.05$).

## RESULTS AND DISCUSSION

Soil disturbances in skid trails during a log-skidding operation by a farm tractor were measured by considering soil compaction and rut depth formation. Field measurements were made at five cross sections along the skid road. The study showed that the vehicle passes had a significant effect on soil compaction; in fact, the results indicated that soil compaction and rutting both increased as the number of passes increased. The analysis revealed that key soil characteristics (moisture, bulk density, porosity and penetration resistance) of the timber harvesting plots were all significantly different from those of the non-harvested plots (i.e. control) (Table 2). The post-hoc Tukey test detected significant differences in all parameters studied between the different traffic levels and the control ($p < 0.05$).

**Table 2.** Soil characteristics (Soil Moisture %; Bulk Density g $cm^{-1}$; Total Porosity %; Penetration Resistance kPa)

| Number of passes | Number of samples | Moisture | | Bulk density | | Total porosity | | Penetration resistance | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 0 | 50 | $30.34^{a}$ | 2.02 | $0.92^{a}$ | 0.03 | $65.2^{a}$ | 2.99 | $525.6^{a}$ | 9.14 |
| 1 | 100 | $28.36^{b}$ | 1.29 | $0.94^{b}$ | 0.03 | $64.4^{b}$ | 3.44 | $1,632.4^{b}$ | 4.76 |
| 5 | 100 | $26.76^{c}$ | 1.14 | $0.966^{c}$ | 0.02 | $64.6^{c}$ | 4.96 | $1,813.9^{c}$ | 96.87 |
| 10 | 100 | $14.32^{d}$ | 0.92 | $1.046^{d}$ | 0.05 | $61.4^{d}$ | 5.68 | $2,358.5^{d}$ | 166.38 |
| 15 | 100 | $11.47^{e}$ | 1.34 | $1.162^{e}$ | 0.04 | $56.2^{e}$ | 3.49 | $2,504.6^{e}$ | 186.16 |

Table 3 shows the results of the ANOVAs for the four soil response variables. The ANOVA suggest there was much random variation in the data, which is perhaps expected in a diffused sampling approach. Sampling points are likely to hit trafficked as well as intact areas within the same sample plot, and this coincidence may explain the high random variation. At the same time, the sampling intensity was sufficient to capture a significant difference among the treatment levels, as indicated by the very low $p$-values.

The effect of soil compaction on the soil moisture content was significant ($p < 0.01$). Specifically, the results show a reduction in water content in the skid trail. This decrease was directly proportional to the number of passes; in fact, the average moisture content was 11.47% on the tractor trail (after 15 passes) versus 30.34% in the undisturbed area (Fig. 3). Previous studies (Raghavan et al., 1977; Davies et al., 1973) have identified wheel slip on agricultural tractors as culprits that cause significant soil compaction, and wheel slip from forest vehicles can presumably also contribute to such compaction.

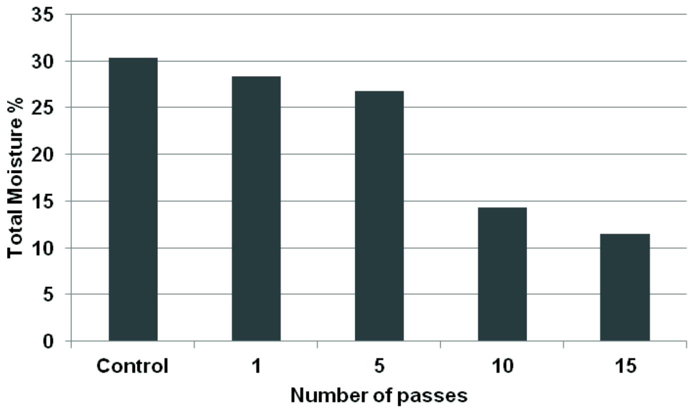


**Figure 3.** Soil moisture (%) compared to the previous number of machine passes.

Soil compaction caused by skidding reduced the average moisture content in the skid road. In the tracks of the tractor, soil moisture content were low because of less pore space available for water infiltration and retention at elevated bulk density levels. This could be due to the forest floor removal and consequences of a reduced water infiltration rate. Our findings agree with those of Tan et al. (2005), who reported that soil compaction reduced soil moisture content by 11% after forest floor removal. Carter & Shaw (2002) reported that the moisture content decreased with an increase in soil bulk density due to a decrease in soil porosity and the infiltration rate.

Average soil bulk density in the tractor trail ranged from 0.94 g $cm^{-3}$ to 1.16 g $cm^{-3}$, while it was 0.92 g $cm^{-3}$ in the undisturbed plot. Soil compaction increased with more passes made; indeed, the bulk density was influenced significantly by the traffic frequency ($p < 0.01$). Carter & Shaw (2002) reported significant negative correlations between soil bulk density and soil moisture content. A negative correlation between bulk density and soil moisture content would suggest a potential decrease in soil moisture at higher bulk densities, presumably due to soil compaction. Total porosity was considerably lower than the total porosity in the undisturbed plot, and this response variable decreased with the tractor traffic frequency. Porosity is inversely related to bulk density; this means that a decrease in porosity entails an increase in bulk density after the tractor passes. The total porosity was influenced significantly by the number of passes ($p < 0.01$).

In a highly productive Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stand in northwest USA. Ares et al. (2005) found that ground-based logging caused, on average, a 27% increase in the soil bulk density and 10% –13% reduction in the soil porosity. At our forest site in Italy, the recorded values for penetration resistance were greatest after 10 and 15 passes as compared to the 1 and 5 passes and the control ($p < 0.01$). The mean values of penetration resistance in the tractor trail range from 1,632.4 kPa to 2,504.6 kPa, with a value of 525.6 kPa in the undisturbed plot (Fig. 4).

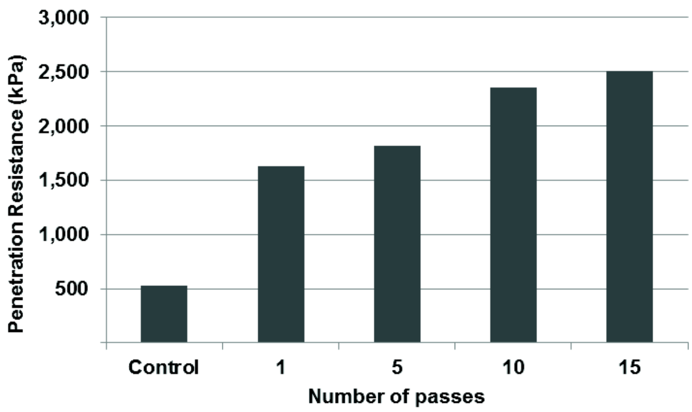


**Figure 4.** Penetration Resistance (kPa) compared to the previous number of machine passes.

**Table 3.** ANOVA for Moisture, Bulk Density, Porosity and Penetration Resistance

| | | | | | |
|---|---|---|---|---|---|
| Moisture | | | | | |
| | Sum of squares | df | Mean square | F | Sig. |
| Between groups | 1,510.906 | 4 | 377.727 | 155.979 | 0.000 |
| Within groups | 48.433 | 20 | 2.422 | | |
| Total | 1,559.339 | 24 | | | |
| Bulk Density | | | | | |
| | Sum of squares | df | Mean square | F | Sig. |
| Between groups | 0.196 | 4 | 0.049 | 32.607 | 0.000 |
| Within groups | 0.030 | 20 | 0.002 | | |
| Total | 0.227 | 24 | | | |
| Porosity | | | | | |
| | Sum of squares | df | Mean square | F | Sig. |
| Between groups | 280.560 | 4 | 70.140 | 3.123 | 0.038 |
| Within groups | 449.200 | 20 | 22.460 | | |
| Total | 729.760 | 24 | | | |
| Penetration Resistance | | | | | |
| | Sum of squares | df | Mean square | F | Sig. |
| Between groups | 12,276,069.952 | 4 | 3,069,017,488 | 170.907 | 0.000 |
| Within groups | 359,144.829 | 20 | 17,957.241 | | |
| Total | 12,635,214.780 | 24 | | | |

Root growth is typically restricted following compaction due to the increased penetration resistance of soil (Wasterlund, 1985; Taylor & Brar, 1991). For many tree species, their root growth is limited when the soil penetration resistance exceeds 2.5 MPa (Greacen & Sands, 1980; Whalley et al., 1995), a threshold that is often reached during forest timber harvesting. Our data show that after 15 passes this value was in fact reached.

Hence, it is clear that the number of machine passes is a key factor that significantly influences the degree of soil damage. Many (e.g. Froehlich, 1978; Brais, 2001) have studied the impact of the frequency of vehicle passes on soil compaction, finding that it occurs mostly during the first few passes of a vehicle. Subsequent passes have a smaller effect, but they may nonetheless increase bulk density levels and reduce porosity to levels critical for absolute tree growth (McNabb et al., 1997). Reduction in soil porosity as implied by compaction imposed by machine traffic in forest soilsmay amount to 50%–60% (Ares, et al.; 2005; Demir et al., 2007; Frey et al., 2009; Proto, et al., 2016b; Solgi & Najafi, 2014). Such a reduction chiefly occurs at the expense of macropores, which function in promoting soil drainage Seixas & McDonald, 1997; Ampoorter et al., 2007). Several studies (Williamson & Neilsen, 2000) have reported than ta reduction of total porosity after machine traffic 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.

Our results indicated that the ruts deepened after 1, 5, 10, and 15 passes for skid road, reaching maximum depths of 2.2, 2.8, 3.6, 4.1, and 4.7 cm, respectively. In a similar study to ours, Ozturk (2016) reported an average rut depth of 3.5–4.6 cm after 8–16 tractor passes during a log skidding operation. The weight of a loaded vehicle and the number of passes are major factors influencing the rut formation (Jansson & Johansson, 1998; Bygdén et al., 2004; Eliasson, 2005). Ruts are usually more marked by wheeled vehicles than by tracked vehicles, due to the higher pressure on the soil, and for moist soil than for dry soil, due to the lubricating action of water on soil particles (Marchi et al., 2014). When they occur, abundant rains may saturate the soil contiguous to ruts, thus hastening the risk of mud-flows or landslides. As ruts are preferential paths for surface runoff, in steep terrain they may become dangerous foci for erosion (i.e., gullies) (Startsev and McNabb, 2000; Christopher & Visser, 2007). When air-filled porosity falls below 10% of the total soil volume, microbial activity and plant growth can be severely limited in such most soils (Brady & Weil, 2002). The negative impacts of wheeling tracks in forest soils upon soil aeration that control the respiration processes of microorganisms have been documented by Schaffer et al. (2001).

These above effects of soil disturbance may well persist for several decades because of very slow forest recovery rates (Corns, 1988; Shepperd, 1993; Grigal, 2000). In fact, the time necessary for impacted soils to recover to their original physical state is variable, and also will depend on their depth.

The starting point for limiting impact of machinery traffic on a forest ecosystem is a good knowledge of the area involved to better calibrate interventions based on the susceptibility of the environment to damage, as well as its resilience. In particular, the decision of whether or not to use heavy vehicles should rely on an accurate site-level risk assessment for soil aided by a geographic information system. Furthermore, the skidding operations should be thoughtfully planned and carried out when soil conditions are dry, to minimize rutting; but if skidding must be done under wet conditions, the operations should be stopped once deep ruts are evident from machine traffic.

## CONCLUSION

This research investigated the conventional factors impacting soil during forest logging operations that rely on a farm tractor. Nevertheless, this study was conducted with the overall objective of characterizing the effects of tractor farm passes – the primary extraction method 'traditional' in the forests of the Southern Italy – on soil disturbance at different levels of traffic intensity. The results clearly show that soil moisture content, bulk density, total porosity, and penetration resistance could all be used as robust indicators for monitoring harvesting impacts upon susceptible soils. The ensuing soil disturbance and rutting from skidding operations in forestry are prime examples of damage to soil on skid roads. The consequences of soil disturbance by the traffic of harvest machinery can persist for several years, or even decades. The most options to limit the negative effects of heavy logging machinery on susceptible soils appear to be:

- ✓ leaving more woody residue on the ground for topsoil reinforcement;
- ✓ reducing as much as possible the contact pressure between moving machines and the soil beneath them;
- ✓ waiting for relatively dry soil conditions when the load-bearing capacity of the soil is higher, and planning the logging design accordingly;
- ✓ avoid generating traffic whenever the soil water content is very high.

Finally, it is worthwhile to remember that designated skid trails should be used to reduce potential soil compaction in logging operations, and to thus preserve the rest of the forest area.

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