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IMPACT OF FOREST OPERATION ON SOIL COMPACTION – SAN ROSSORE CASE STUDY

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Abstract

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The paper presents the assessment of compaction grade caused by machinery used in forest biomass for energy harvesting. The main aim was to determinate unaffected soil conditions, the compaction grade exactly after harvesting activities, the return of soil after couple of years and compaction grade in stands, which were not harvested but affected by skidding and seed collection activities. Therefore four different compaction grades were evaluated. To ensure as much as possible uniform soil conditions also soil samples were evaluated. Soil samples were collected using Kopecky physical metal rings and followed characteristics of soil were determined i.e. moisture content, bulk density and porosity, respectively. In San Rossore national park 24 plots were identified of which 8 were harvested in 2011 year (H2011), 8 were harvested in 2005 year (H2005), 7 were not harvested but were affected by other activities (NH) and 1 was unaffected (U). On each plot 50 repetition of measurement were carried out. The results display both: significantly different compaction grade of soil and return of the soil towards the original conditions after 6 years.

Keywords: soil compaction, San Rossore, forest biomass, soil return, penetration resistance

INTRODUCTION

Actually high demands are put on the forestry sector with respect to processing of timber for energy use. The source of the material for energy can be found also in national parks, where also treatments of stand are necessary. One of the ways how to effectively use harvested volume is to sell it for energy. Also other activities such as seed collection, transport of any good etc. are carried out to support economy of the national park. However, any of those activities negatively affect the soil and trees. Any of soil physical conditions change (porosity, aerating) may impact growing and development of root system. Gebauer and Martínková (2005) presented the development of spruce root system which grew in compacted soil and found significantly lower (38%) root system area. The root growing in soil needs to overpower axial and radial soil pressure and soil friction Greacen (1986).

Synergy problem of compaction by heavy logging system passing on strip roads is rutting. Compaction may activate disturbances in gas exchange in soil. In case when the exchange of gases in soil is reduced, carbon dioxide ventilation decreases and therefore its accumulation in soil increases Neruda (2010). This affects both soil organisms activity which is corresponding to soil structure and moisture content, but also income of nutrition, respectively.

Quality of the soil is topic which becomes on popularity. Generally, the quality is assessed using three main aspects: physical, chemical and biological. Those aspects are considered to be important for assessment of soil degradation or amelioration and also for identification of management method ensuring sustainable soil exploitation. According to Dexter (2004) soil physical conditions seems to be however the most important, because they have high impact on chemical and biological processes in soil.

Forest soil is poly-dispersive system, where the basic is in spatial arrangement of primary and secondary structure of elements; those elements compose from soil particles of different size, I: *Critical values of specified soil physical characteristics (Lhotsky, 2000)*

	Soil type (volume of particles less than 0.01 mm in %)					
	Clay (> 75)	**Till to clay-loam (75–46)**	**Argilaceous (45–31)**	**Sandy loam (30–21)**	**Sabulous (20–11)**	**Sandy (< 10)**
Basic density (g.cm^{-3})	> 1.35	> 1.40	> 1.45	> 1.55	> 1.60	> 1.70
Porosity	< 48	< 47	< 45	< 42	< 40	< 38
Penetration resistance (MPa)	2.8–3.2	3.3–3.7	3.8–4.2	4.5–5.0	5.5	> 6.0
By moisture content	28–24	24–20	18–16	15–13	12	10

shape and characteristics. From this point of view the forest soil can be described using physical characteristics which are colour, texture, porosity, consistence and structure (Rejšek, 1999). Those specific characteristics are dependent on interaction between solid, liquid and fluid elements.

The critical values of selected soil physical characteristics according to Lhotsky (2000) are presented in Tab. I. If those values are exceeded, the plants and also microedaphon is negatively affected immediately.

Ampoorter (2010) presented, that regeneration is of long duration process which is based on frizzing and melting of soil water, swelling up and shrinkage of soil particles and biological activity of roots and soil organisms. The soil regeneration in natural conditions is of long duration, in average 10 to 15 years and more. Literature presents also highly time demanding regeneration process according to soil type. Shaffer (2005) presented that duration 30–40 years was not enough to fully restore gas diffusion and root hair density in footprint. Disturbance of soil activity is very difficult to measure in reality. The supporting values are therefore used, for example increase of soil density, soil moisture content, volume of pores, water infiltration, air respiration and other.

Compaction caused by machinery, number of passes, soil type and moisture content all those play role. Finally, no simple and exact device for compaction measuring on forest soils is available. Different authors were using various devices such as deflectometer (Klvač *et al.* 2010), permeameter (Buchar, 2011), penetrometer etc. However, application of the penetrometer on soil without large fraction and without heavy rootiness seems to be the best option from the time consumption and data quality point of view. The soil in San Rossore national park was sandy and therefore authors have chosen cone penetrometer with ability to continuously record data (penetrologger Eikelkamp).

The main aim was to determinate compaction grade after harvesting operation and without harvesting operation but affected by other activities. The second aim was to identify if the soil embodies the return after couple of years. To be able to compare the results also unaffected soil (reference area) had to be measured.

MATERIAL AND METHODS

The survey area was chosen in nature park San Rossore near Pisa. 24 plots were identified of which 8 were harvested in 2011 year (H2011), 8 were harvested in 2005 year (H2005), 7 were not harvested but were affected by other activities (NH) and 1 was unaffected (U).

The stands were originally all overmature umbrella pine (*Pinus pinea* L.) plantations, aged between 100 and 150 years. They were clearcut and yielded between 250 and 350 tons of biomass per hectare. Stand density was about 200 trees per hectare.

Umbrella pine trees grew on loamy sand, developed over a quaternary dune just few kilometres from the present coastline. Under these conditions, soil drainage characteristics depend on the micro-relief: the old dune tops drain very easily, whereas the small hollows between them tend to retain water and fill with clay. For this reason, pine is only planted on the dune tops, while the hollows are left to the natural regeneration of hygrophilous hardwood species. All plots were chosen in as much as possible uniform umbrella pine stands.

Plots harvested in 2005 or 2011 – Trees were felled with a 20-t tracked feller-buncher, equipped with a high-speed disc saw (hot saw). The feller-buncher also performed a rough debranching and crosscutting, using a special articulated joint on the boom, which allowed turning and tilting the disc saw. Basal logs were crosscut in 4 to 5 m random lengths, and extracted to roadside using an 8-wheel drive forwarder, with a 14-t load capacity. Branches and tops where chipped on site using a forwarder-mounted chipper, powered by a 350 kW independent engine. Chips were discharged into three-axle silage trailers with a 10-ton payload capacity, towed by 100-kW four-wheel-drive farm tractors.

Non-harvested plots but affected by other operation were located under the mature pine stand. Those plots, however, were severally passed by machinery transporting any of goods such as roundwood or chips, shaking machinery used due to the seed collection etc.

The unaffected plot was under the mature pine stand. According to personal communication with director of the national park and also according to ocular observation no activities were carried out in this stand.

The compaction grade caused by machinery was measured by a cone penetrometer (penetrologger Eikelkamp). Penetration resistance was measured in 50 repetitions. The work procedure of measuring by penetrometer presented by Matys *et al.* (1990) was slightly modified for manual penetrometer. Soil bearing capacity was measured by using a cone type with 1 cm^2 cone base area and 60° top angle. The values of soil resistance to the penetrating point were measured by the pressure gauge (instrument part). The penetration rate was approximately 2 cm per second – with equal pressure exerted onto both handles. The device automatically recalculated the penetration force from tensometer and recorded data in MPa in each centimetre of the deepness. The soil compaction was measured up to 40 cm of the deepness. After each plot measurement the cone was validated with calibre (part of equipment provided by manufacturer). *Note: In average the cone had to be replaced after 600 of measurements.*

To ensure as much as possible uniform soil condition or to support the results of penetration resistance also the Kopecky physical metal rings were collected on each plot after raw material removing. All samples were hermetically enclosed and moved into the laboratory. Wet soil samples were weighed in laboratory conditions with the accuracy of grams and inserted into an oven where they were dried at a temperature of 105 °C (+/–2°C) for 8 hours. Then the soil samples were weighed in dry condition and moisture contents of soils in the individual sites were calculated. The porosity was investigated using pictometers. On each site 10 samples were collected.

The initial analysis was made with the use of pivoting tables and graphs. Relations and dependencies between the depth and penetration resistance were assessed by using the programme GraphPad Prism 5. The GraphPad Prism 5 (Motulsky, 2007) was used for non-linear regressions. The software enables a very flexible choice of the regression model, has very good graphical capabilities and it is possible to compute and draw confidence intervals of the model (this feature still being rare in non-linear model software). Prism 5 can eliminate outliers with the ROUT method (Motulsky and Brown, 2006). This method is based on a new robust non-linear regression combined with outliers rejection. It is an adaptive method that gradually becomes more robust as the method proceeds. Based on a suggestion of Press *et al.* (1988) they based their robust fitting method on the assumption that variation around the curve follows a Lorentzian distribution rather than a Gaussian distribution. The Marquardt non-linear regression algorithm was adapted to accommodate the assumption of a Lorentzian (rather than Gaussian) distribution of residuals. After fitting a curve using robust non-linear regression, a threshold is needed for deciding when a point is far enough from the curve to be declared an outlier. All methodology is described in detail in Motulsky and Brown (2006). The authors state that their method identifies outliers from non-linear curve fits with reasonable power and few false positives (less than 1%).

In all cases, the exponential function used for the regression model was in the following form:

$$y = a \cdot x^b, \qquad (1)$$

where
x .... explaining (independent) variable,
y .... explained (dependent) variable,
a, b ... coefficients.

The respective statistical assessments include *a*, *b* coefficients established by the regression analysis, 95% confidence interval (shaded in the final graph), R^2 – determination coefficient, number of analyzed points and number of outliers.

Secondly one way ANOVA was carried on the treatment types, where 7 or 8 plots were measured to determinate significance/insignificance between measurements.

RESULTS

Each treatment was evaluated separately what is presented on Figs. 1–4. Harvested area in 2011 (H2011 – Fig. 1) shows, that from 8 sample plots only one is slightly less compacted. Other 7 plots are almost at the same level. The compaction in 40 cm rose up to 6 MPa, which is according to Lhotsky (2000) critical value indicating compaction of the sandy soil.

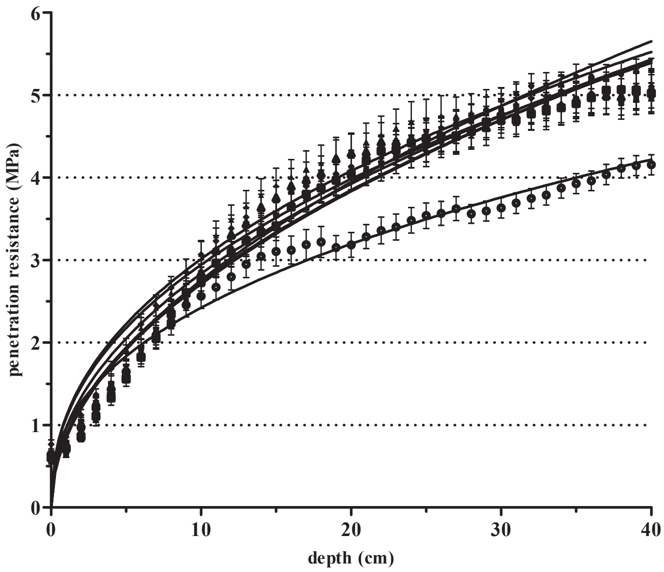
The same type of operation was carried out also in year 2005. However, areas harvested in 2005 (H2005 – Fig. 2) were regenerating 7 years, which is visible on chart. Individual curves vary quite a lot. Some of plots indicates soil regeneration more intensively, some of them less.

Detailed statistics analyzes is presented in Tab. II (for areas harvested in 2011) and Tab. III (for areas harvested in 2005). One way ANOVA analyzes for areas harvested in 2005 showed, that the mean values vary significantly, which also indicates different regeneration process on individual plots (Tab. V).

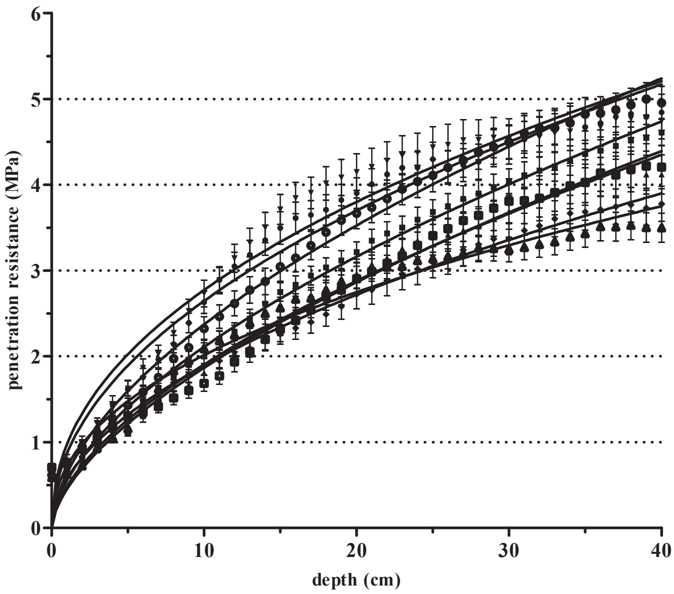
Curves representing plots from areas which were not harvested (NH), but other activities was carried out here are presented in Fig. 3. From this chart can be figured out, that all non harvested plots were disturbed by other activities differently. The grade of compaction probably varies with proportion of those activities. The unaffected area presented on Fig. 4 is visibly without effect of compaction and the value in 40 cm reaches only up to 2.5 MPa.

Detailed statistics analyzes of non harvested and of unaffected areas is presented in Tab. IV. One way ANOVA analyzes for non harvested areas displays heterogeneity (Tab. V). The unaffected area was only one plot, therefore one way ANOVA may not be carried out.

Finally, based on the analyzes of each treatment type and based on the statistics, each results for individual treatment type may be called as



1: *Compaction grade on harvested areas in 2011 (H2011)*



2: *Compaction grade on harvested areas in 2005 after 7 years of soil regeneration (H2005)*

II: *Results of regression analyses of compaction grade on harvested areas in 2011*

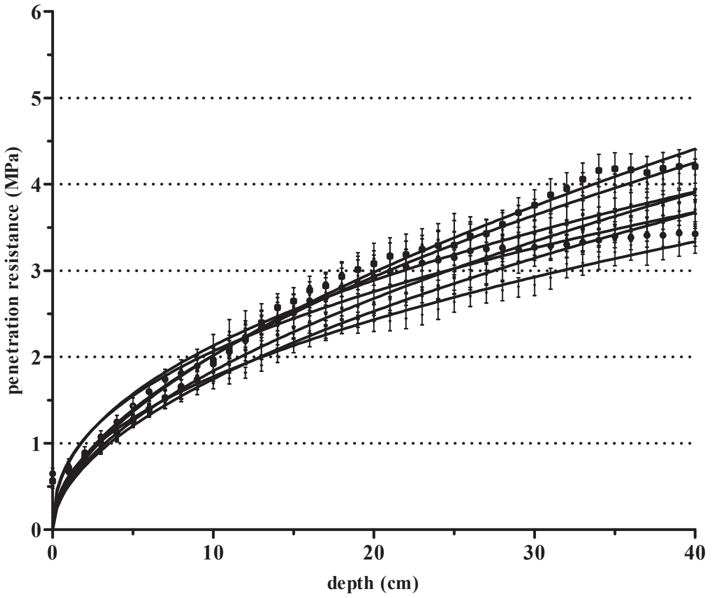
Plot ID	* Regression coefficients of equation $y = a \cdot x^b$		Border coefficients, 95% Confidence Intervals		R^2	Analyzed points/ No. of outliers
	a	b	a	b		
Plot 1	0.8347	0.5185	0.7748 to 0.8946	0.4964 to 0.5407	0.6710	2028/0
Plot 2	0.8748	0.4944	0.7949 to 0.9546	0.4662 to 0.5226	0.5364	2040/0
Plot 3	1.101	0.4373	1.002 to 1.199	0.4092 to 0.4655	0.4779	2002/0
Plot 4	0.8748	0.4944	0.7949 to 0.9546	0.4662 to 0.5226	0.5364	2040/0
Plot 5	1.077	0.4364	0.9935 to 1.161	0.4120 to 0.4608	0.5385	1994/02
Plot 6	0.9142	0.4126	0.8496 to 0.9788	0.3905 to 0.4348	0.5559	1983/22
Plot 7	0.8544	0.5011	0.7757 to 0.9331	0.4725 to 0.5296	0.5389	2011/0
Plot 8	0.9630	0.4689	0.8706 to 1.055	0.4391 to 0.4987	0.4832	2008/0

* x – depth (cm), y – penetration resistance (MPa)

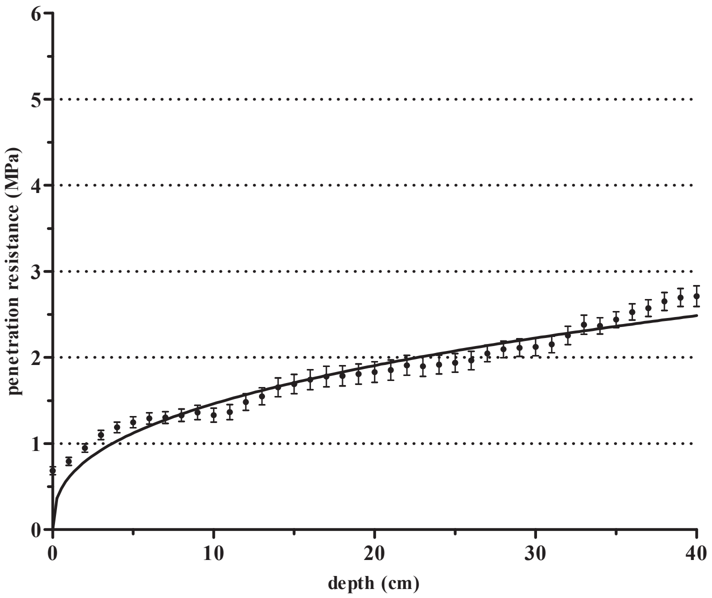
III: *Results of regression analyses of compaction grade on harvested areas in 2005*

Plot ID	* Regression coefficients of equation $y = a \cdot x^b$		Border coefficients, 95% Confidence Intervals		R^2	Analyzed points/ No. of outliers
	a	b	a	b		
Plot 1	0.8639	0.4850	0.7863 to 0.9415	0.4570 to 0.5130	0.5325	1959/2
Plot 2	0.5510	0.5832	0.5051 to 0.5970	0.5578 to 0.6087	0.6571	2050/0
Plot 3	0.4841	0.5952	0.4240 to 0.5442	0.5573 to 0.6330	0.4685	2050/0
Plot 4	0.9742	0.4545	0.8799 to 1.068	0.4244 to 0.4846	0.4586	2037/0
Plot 5	0.5928	0.5031	0.5294 to 0.6561	0.4700 to 0.5361	0.4424	2027/19
Plot 6	0.6364	0.5715	0.5742 to 0.6987	0.5415 to 0.6015	0.5734	2038/0
Plot 7	0.4507	0.6172	0.3861 to 0.5154	0.5735 to 0.6610	0.4126	2037/0
Plot 8	0.7180	0.4481	0.6543 to 0.7817	0.4205 to 0.4757	0.4856	2042/0

* x – depth (cm), y – penetration resistance (MPa)



3: *Compaction grade on non harvested areas (NH)*

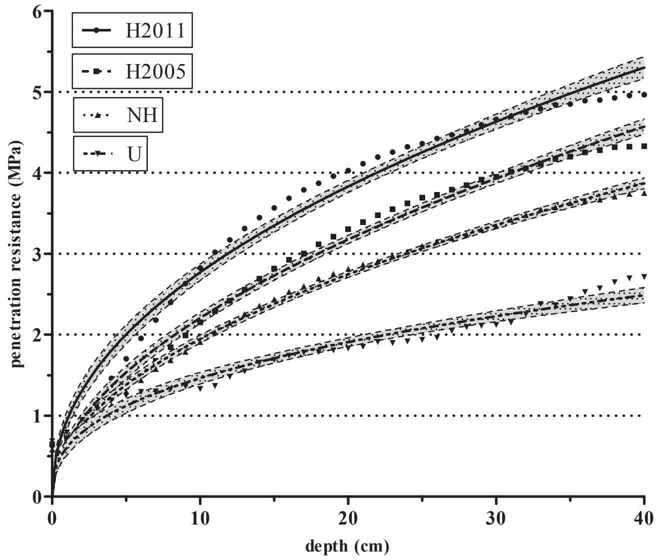


4: *Unaffected soil (U)*

IV: *Results of regression analyses of compaction grade on non harvested areas and on unaffected area*

Plot ID	* Regression coefficients of equation $y = a \cdot x^b$		Border coefficients, 95% Confidence Intervals		R^2	Analyzed points/ No. of outliers
	a	b	a	b		
Plot 1 NH	0.7765	0.4385	0.7007 to 0.8522	0.4080 to 0.4689	0.4264	2020/62
Plot 2 NH	0.5255	0.5436	0.4736 to 0.5774	0.5132 to 0.5739	0.5270	2038/57
Plot 3 NH	0.5856	0.5374	0.5224 to 0.6488	0.5041 to 0.5706	0.4900	2001/20
Plot 4 NH	0.6196	0.4563	0.5674 to 0.6718	0.4301 to 0.4825	0.5113	2034/5
Plot 5 NH	0.5066	0.5368	0.4636 to 0.5495	0.5108 to 0.5629	0.5905	2049/5
Plot 6 NH	0.7939	0.4155	0.7184 to 0.8694	0.3858 to 0.4452	0.4027	2050/0
Plot 7 NH	0.5504	0.5640	0.4933 to 0.6076	0.5322 to 0.5958	0.5324	2039/0
Unaffected	0.6056	0.3829	0.5499 to 0.6613	0.3540 to 0.4117	0.3343	2043/0

* x – depth (cm), y – penetration resistance (MPa)



5: *Mean values for each of the treatment (U – unaffected, NH – non harvested, H2005 – harvested in 2005 and H2011 – harvested in 2011)*

V: *One way ANOVA results*

Treat. type	ANOVA			Bartlett's test		SS	No. of groups
	P	R^2	Are means signif. different? ($P < 0.05$)	P	Do the variances differ signif. ($P < 0.05$)		
H2011	0.1769	0.03117	No	0.3942	No	18.06	8
H2005	< 0.0001	0.09632	Yes	0.1288	No	46.77	8
NH	0.1240	0.03490	No	0.2738	No	9.282	7

representative for this soil type. To be able to generally compare all types of the treatment, average values from all repetition were drawn in chart and evaluated using non-linear regression. This comparison is presented on Fig. 5. The curves on Fig. 5 are represented by following equations:

$$\text{H2011: } y = 0.9422 \cdot x^{0.4682} \quad (2)$$

$$\text{H2005: } y = 0.6573 \cdot x^{0.5257} \quad (3)$$

$$\text{NH: } y = 0.62 \cdot x^{0.4964} \quad (4)$$

$$\text{U: } y = 0.6046 \cdot x^{0.3835} \quad (5)$$

For each curve the determination coefficient (R^2) reached at least 0.9.

The results of laboratory analyzes of soil samples collected using Kopecky physical metal rings are presented in Tab. VI. The moisture content was almost uniform across all the plots, which ensured uniformity of initial soil conditions. However, soil bulk density and porosity correlate with the results obtained from penetration. The higher compaction of the soil the higher bulk density; and the higher compaction grade the lower porosity.

VI: *Results of laboratory tests of soil obtained from Kopecky physical metal rings*

Treat. type	Moisture content dry basis (%)	Bulk density reduced (g.cm^{-3})	Porosity (%)
H2011	5.8	1.38	46.0
H2005	5.4	1.38	47.7
NH	4.5	1.28	50.7
U	4.3	1.26	53.1

DISCUSSION

Finding of clearly unaffected soil in the region of the national park San Rossore is very complicated. Plenty of activities such as treatment of the stands, silviculture of the stands, harvesting activities, tourism and/or game management highly impact almost all the area. Therefore only one plot located near to the other was identified as unaffected. However, authors cannot fully ensure that this plot is really without any of impact.

The results from both penetration resistance and soil samples analyzes give expected grades of compaction with respect to treatment type. In higher layers of soil is the difference smaller and with increasing deepness of the soil layers the difference between compaction grade is more visible.

Comparing compaction grade on harvested areas the return of soil into the natural condition is visible even if the soil regenerated only 6 years. This statement is based on presumption, that the same technology was used for harvesting operation on both areas (director of San Rossore national park – personal communication). The intensity of the harvesting operation is hard to compare, but the age of stands rose up only from 6 years which should not affect to much average tree volume when trees are more than 100 years old.

Any of soil type, mainly sandy soil wears the cone. Therefore after each of plot measurement process the cone was verified with caliber. In average the cone was replaced every 600 measurements. Founder decrease of cone diameter was from 11.39 to 11.31 mm, which resulted by 1% smaller cone contact surface. This wear was insignificant from our measurement results point of view.

CONCLUSION

Forest operation in mature umbrella pine stands produces significant alterations of soil physical characteristics, additional to those eventually caused by other management activities. However, the extent of these alterations is below critical limits after couple of years, partly due to the sandy soil resistance to compaction. What is more, recovery seem to be relatively fast. Six years after harvesting, soil conductivity is back to the original pre-harvest values, which is likely to accelerate the further restoration of original soil characteristics.

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