Soil Compaction and Recovery after Mechanized Final Felling of Italian Coastal Pine Plantations

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Abstract

This study gauged the severity and permanence of soil compaction associated with mechanized clear felling of umbrella pine plantations. We tested three treatments: not harvested, harvested one year earlier and harvested six years earlier. Each treatment was replicated eight times in randomly distributed 0.5 ha plots, on the same soil type. Soil compaction was assessed by gauging soil bulk density, penetration resistance, deflection under impact and CO_2 concentration. These parameters were measured with steel rings, penetrometer, deflectometer and soil air analyzer, respectively. Measurements were conducted on 8 clear cut blocks per treatment, which had been randomly distributed over the same forest, with identical soil and stand type. One year after clear fell, bulk density increased by 9%, penetration resistance by 50% and deflection by 60%. Porosity decreased by 10%, which entailed a parallel 30% increase of both soil moisture content and CO_2 concentration in the soil air. Six years after clear fell, there was no sign of recovery for bulk density, deflection and moisture content. On the contrary, penetration resistance was significantly reduced, and CO_2 concentration was back to the values recorded in plots that had not been harvested.

Keywords: harvesting, disturbance, clear fell, impact

1. Introduction

Rising labour cost and global competition have eroded the economic sustainability of traditional wood harvesting technology. Forest management is increasingly mechanized in all industrial countries, where animal power (Magagnotti and Spinelli 2011) or small scale forest technology (Vusić et al. 2013) are only profitable under specific circumstances. In turn, the rapid progress of mechanized harvesting has brought about an increased awareness of the potential site impact generated by industrial forest technology, and by forest operations in general.

Many forest owners fear that the large size and heavy weight of modern machinery may determine a significant increase of stand and soil impacts, compared to traditional motor manual operations (Vokoun et al. 2006). Foresters feel especially uneasy about the difficulty in detecting and predicting soil compaction, whose occurrence may elude visual inspection, at least initially and until its consequences become apparent (Horn et al. 2004). Traffic is particularly heavy in clear fell operations, due to the larger size of machinery and larger removal (Marchi et al. 2011). Soil compaction may cause physiological stress in the tree or seedling, reducing its ability to cope with adverse climatic conditions and/or to compete with other vegetation. Fortunately, physical and biological agents will eventually loosen up the soil, leading to recovery. However, this process may take considerable time, which is particularly worrying for intensely managed stands, entered several times during a rotation (Grigal 2000).

The occurrence, severity and persistence of soil compaction are very difficult to predict, since they are the result of a complex interaction of harvest, soil and stand characteristics (Ampoorter et al. 2012). That prevents extrapolating the results of individual studies, as well as formulating generally valid guidelines. Relatively few compaction studies have been conducted in the Mediterranean region (Gondard et al. 2003), partly due to the slower progress of mechanized harvesting. Nevertheless, harvesting operations in Mediterranean forests are often associated with widespread soil disturbance (Spinelli et al. 2010) and compaction (Magagnotti et al. 2012).

Matters become especially complex in coastal pine plantations under multifunctional management, with the multiple goals of timber production, extraction of non-timber products (pine nuts) and recreation (Carrasquinho et al. 2010). On one hand, the forest soil is impacted by more activities than just timber harvesting, which may confound the effects; on the other hand, the impact of harvesting is under severe scrutiny due to the intense public frequentation. Therefore, the goals of this study were:

⇒ to quantify the extent of soil compaction associated to the clear felling of coastal pine plantations;

⇒ to gauge soil recovery years after clear felling.

2. Materials

A trial was carried out in the Regional Park of San Rossore, near Pisa, on the Tyrrhenian coast. The park encloses a surface of about 3 000 ha and is mostly covered by pine plantations (Spinelli et al. 2009). All forests inside the park are protected and under a special management regime. Careful exploitation is conducted according to sustainable management rules. All harvesting is completely mechanized, with the intent of enhancing worker safety and minimizing operation residence time, to the benefit of the intense recreational use. The trial was conducted in October 2012 on 24 plots, equally divided into the following three treatments: not harvested, clear felled one year earlier (2011) and clear felled six years earlier (2005). All plots represented mature umbrella pine (*Pinus pinea* L.) plantations, with an age of about 100 years. Stand density and stocking were in the range of 200 trees ha^{-1} and 320 tons ha^{-1}, respectively. Umbrella pine trees grew on loamy sand, developed over a quaternary dune just a few kilometers 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. Test plot selection was done after consulting the local soil map, in order to probe plots growing on exactly the same soil type, in this case a Typic Udipsamment (USDA 1999). Soil texture was sandy (86% sand, 3% silt, 11% clay), with an organic matter content of about 3%. Each plot represented one clear cut block, with a surface of about 5 000 m^2. Plots were laid out in an alternate sequence because of the prescribed felling pattern, aimed at maintaining some form of lateral cover to mitigate visual impact and prevent windthrow in non-harvest areas (Spinelli et al. 2013). Control plots were represented by the blocks that had not been clear felled yet.

All 16 cut plots were clear felled with the same method and technology, applied by the same company and the same machine operators. Trees were felled with a 27 tons 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 tonne load capacity. Branches and tops where chipped inside the blocks using a forwarder mounted chipper, powered by a 350 kW independent engine. Chips were discharged into three axle silage trailers with a 10 tonne payload capacity, towed by 100 kW four wheel drive farm tractors, for extraction to the roadside. The total weight of loaded machines was: 27 tons for the tracked feller buncher, 30 tons for the loaded forwarder, 30 tons for the forwarder mounted chippers and 22 tons for the tractor and trailer chip shuttling units. All forwarders were equipped with 700 mm tires, inflated at a 450 kPa. Tractor trailers were equipped with 380 mm tires, also inflated at 450 kPa.

At the time of data collection, the plots clear felled in 2005 had already been replanted with pine seedling, set 3.5 m apart. Plantation had been conducted manually, and consisted in the localized opening of a fissure for inserting the seedling. The soil had not been tilled or disturbed by machinery during planting operations, and it was invariably covered by a dense brush layer about 1 m tall. The plots clear felled in 2011 had not been replanted yet, but the brush was starting to come up, although not as densely as in the 2005 plots. In both cases, it was very difficult to detect any tracks, or other visible signs of machine traffic, except for occasional diffused wood chip spills, indicating the stations of the forwarder mounted chipper. Therefore, it was impossible to differentiate between inside track and outside track sample points, and we opted for a diffused systematic sample pattern.

3. Methods

Soil compaction was determined concurrently with four different methods, with the goal of implementing a robust experimental setup, capable of internal corroboration and multiple detection capacity, where the effects that may elude one method are captured by the others. Therefore, soil compaction was gauged through:

⇒ bulk density;
⇒ penetration resistance;
⇒ soil deflection;
⇒ soil CO_2 concentration.

Core samples were collected in rings of thin walled stainless steel tubing, with an internal diameter of 8 cm and a height of 5 cm, corresponding to a volume of 250 cm^3. Rings were pushed into the soil down to a 10 cm depth, after removing the litter layer and the first 5 cm of soil, where litter elements could be mixed, which could bias the measurements. Besides, this most superficial layer could have been affected by tire slippage, which would loosen the soil rather than compact it, thus potentially masking the compaction caused by machine traffic. Rings were then removed from the soil, for trimming the sample and placing it into a sealed plastic bag. Bags were taken to the laboratory and weighed before and after oven drying at 105°C for 48 hours. Finally, samples were placed in a picnometer. The resulting figures were used to calculate: bulk density (*BD*), solid density (*D*), gravimetric water content and porosity, for each sample. A total of 240 cores were collected, i.e. 10 for each test plot. This method was only used to explore the first 10 cm soil layer, where the main impacts are often concentrated, at least in Mediterranean and sub Mediterranean soils (Makineci et al. 2007, Picchio et al. 2012).

Penetration resistance was measured with a Eijkelkamp Penetrologger cone penetrometer (www.Eijkelkamp.com), on 50 points per plot, for a total of 1 200 measurements. The cone used for the tests had a 1 cm^2 base area and 60° top angle. Penetration rate was approximately 2 cm per second – with equal pressure exerted onto both handles. The instrument automatically recalculated the penetration force from an inbuilt pressure gauge, and recorded data in MPa at one centimeter depth intervals. Penetration resistance was measured up to a 40 cm depth. After completing measurements on one plot, the cone was checked with calliper (provided by manufacturer) in order to determine if the abrasive effect of sand had reduced its base area below acceptable limits for reliable measurement. Worn cones were replaced before sampling the next plot. All penetration tests were conducted during several consecutive days, in order to minimize variations of soil moisture content, which could have biased the results.

Soil deflection was measured with a portable falling weight deflectometer (PFWD) Loadman II (www.al-engineering.fi), on 20 points per plot. The Loadman II PFWD was specifically developed for measuring the rigidity of road pavements, but it was successfully tested for measuring soil bearing capacity and compaction (Klvac et al. 2010). Litter and the first 5 cm of soil were removed before measurement, in order to increase accuracy. Prior to the first measurement, the instrument was calibrated according to the size of the reaction base plate. The diameter of the reaction base plate was 132 mm and the calibration module of elasticity was chosen to be E 160, as advised by the manufacturer. The falling weight induced a non-destructive shock wave spreading in the soil, and evoking a reaction according to soil properties. Soil reaction was measured through accelerometers built into the reaction base plate of the instrument. Deflection was calculated in millimeters and increased with the degree of compaction. Softer uncompacted soil absorbed a larger portion of the energy released by the falling weight, so that deflection was lower.

CO_2 concentration was measured on 10 points per sample plot, using a portable Carbocap GM70 device (www.vaisala.com), fitted with Carbocap GMP221 sensors. Soil air was extracted from a depth of about 10 cm using a cylinder probe, and it was analyzed on the spot with the inbuilt GMP221 sensors. On each measurement point, readings were taken at 1 minute intervals after letting the instrument stabilize for 10 minutes. The 15 minute reading was accepted into the analysis as the reference.

Sample points were evenly distributed across the test plots, using a fixed sampling distance calculated on the basis of the number of sample points and the size of each individual plot.

Data were analyzed with the Statview advanced statistics software. In particular, the software was used for performing unpaired *t* tests and ANOVA post-hoc tests. Distribution histograms were drawn in order to check whether the distribution of experimental data met the normality assumption. Square root and LOG transformations were applied to normalize data sets that violated the normality assumption. The relation between penetration depth and penetration resistance was estimated with GraphPad Prism 5, after eliminating outliers with the ROUT method (Motulsky and Brown 2006).

4. Results

The main results of the study are reported in Table 1. Soil characteristics in clear felled plots were significantly different from those in non-harvested plots. All measures indicated the presence of com-

Table 1 Main results of the study

	OBS	Not harvested		Clear cutting in 2005		Clear cutting in 2011	
	N	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Bulk density, g/cm^3	240	1.277^a	0.134	1.375^b	0.103	1.391^b	0.158
Porosity, %	240	50.9^a	4.5	47.7^b	3.3	46.0^b	4.5
Moisture content, %	240	4.5^a	2.0	5.4^b	2.6	5.9^b	4.5
Penetration resistance at 10 cm depth, MPa	1 200	1.851^a	0.772	2.152^b	0.901	2.824^c	1.128
Penetration resistance at 20 cm depth, MPa	1 200	2.676^a	1.110	3.305^b	1.284	4.028^c	1.402
Penetration resistance at 30 cm depth, MPa	1 200	3.147^a	1.163	3.952^b	1.502	4.661^c	1.391
Penetration resistance at 40 cm depth, MPa	1 100	3.589^a	1.154	4.330^b	1.474	4.967^c	1.270
Soil deflection, mm	480	5.8^a	3.6	9.6^b	3.7	9.3^b	3.7
CO_2 concentration, ppm	240	2 375.1^a	691.0	2 152.1^a	622.4	3 133.0^b	1 312.5

Note: *SD* = Standard Deviation; different letters on the mean values indicate that differences between treatments (figures in the same rows) are statistically significant at the 5% level; *OBS* = observations; *N* = number of observations, which is equally distributed among the three treatments

paction. Compared to non-harvested plots, recently clear felled plots had a 9% higher density, a 50% higher penetration resistance and a 60% higher deflection. Porosity in recently clear felled plots was 10% lower than in non-harvested plots, and both soil moisture content and CO_2 concentration in the soil air were 30% higher.

Plots clear felled six years earlier showed the same differences with non-harvested plots for what concerned bulk density, deflection and moisture content. On the contrary, differences in penetration resistance were significantly smaller, although this parameter was still about 15 to 25% higher than in non-harvested plots. Differences in soil porosity were smaller than for recently clear felled plots, although the statistical significance of differences between recent and older clear fells was borderline (p = 0.066). What is most important, CO_2 concentration was the same as in non-harvested plots.

Table 2 shows the results of the analysis of variance conducted on the study data. The ANOVA shows the very high random variation in the data, which is consistent with a diffused sampling. Sampling points were likely to hit trafficked as well as intact areas within the same sample plot, which explains high random variation. At the same time, sampling intensity was high enough to capture significant differences between treatments, as shown by the very low p Values.

Fig. 1 shows the relationship between penetration resistance and soil depth. Resistance was higher for the clear felled plots, and increased with depth, also due to increased probe friction. In the recently harvested plots, resistance at the 40 cm depth almost reached 6 MPa, which is the critical value indicating

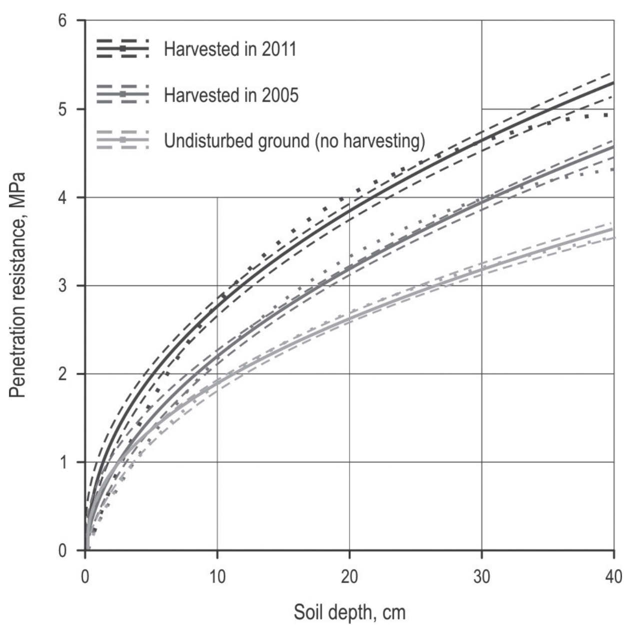

Fig. 1 Relationship between penetration resistance and soil depth

compaction of sandy soil (Lhotsky 2000). Table 3 shows the main parameters for the three regression curves, which have a very good coefficient of determination, also due to the effective elimination of outliers through the ROUT method.

Finally, soil moisture content was significantly higher in the clear felled plots than in the control plots. Higher water retention in the clear felled plots could be related to soil compaction, as well as to evapotranspiration reduction due to the absence of a mature stand.

Table 2 ANOVA table for the main results of the study

	SS	*SS*	σ^2	*F* value	*P* value
Bulk density, g/cm^3					
Treatment	2	0.587	0.13	16.502	<0.0001
Residual	230	4.088	0.87	–	–
Porosity, %					
Treatment	2	504.415	0.20	14.625	<0.0001
Residual	115	1 983.201	0.80	–	–
Moisture content (%) square root transformed					
Treatment	2	2.708	0.04	4.419	<0.0001
Residual	230	70.484	0.96	–	–
Penetration resistance at 10 cm depth (MPa) log transformed					
Treatment	2	6.942	0.15	102.545	<0.0001
Residual	1 197	40.519	0.85	–	–
Penetration resistance at 20 cm depth (MPa) square root transformed					
Treatment	2	27.257	0.15	104.590	<0.0001
Residual	1 197	155.974	0.85	–	–
Penetration resistance at 30 cm depth, MPa					
Treatment	2	452.136	0.17	122.413	<0.0001
Residual	1 197	2 182.880	0.83	–	–
Penetration resistance at 40 cm depth, MPa					
Treatment	2	352.131	0.16	103.310	<0.0001
Residual	1 110	1 891.719	0.84	–	–
Soil deflection, mm					
Treatment	2	1 196.406	0.15	44.307	<0.0001
Residual	501	6 764.088	0.85	–	–
CO_2 concentration (ppm) log transformed					
Treatment	2	0.935	0.18	26.074	<0.0001
Residual	231	4.143	0.82	–	–

Table 3 Main statistics for the regression models shown in Fig. 1

Model type: *PR* = *a* x *Db*						
Parameter	Coefficient	*SE*	95% *CI*	r^2	Valid observations	Outliers
Clear cuttings in 2011						
a	0.942	0.054	0.833 to 1.051	0.972	16 098	24
b	0.468	0.018	0.432 to 0.504			
Clear cuttings in 2005						
a	0.657	0.032	0.592 to 0.722	0.984	16 240	21
b	0.526	0.015	0.495 to 0.556			
Not harvested						
a	0.628	0.025	0.577 to 0.679	0.986	16 274	149
b	0.477	0.012	0.454 to 0.502			

Note: *PR* = Penetration resistance (MPa); *D* = Depth, cm; *SE* = Standard error; *CI* = Confidence interval. The effect of the independent variable is significant at the 1% level.

5. Discussion

In this study, we have used a spatial assumption to represent a time trend. In particular, we have used different plots to represent the state of forest soil at different times with respect to final clear fell. Of course, that is an approximation. The effect of local stand and soil variability could introduce a bias, capable of weakening the results of our study. The same can be said for weather conditions at the time of harvest, which may have differed between the 2005 and the 2011 events. However, we controlled these sources of error by choosing a large number of sample plots in an alternating sequence, with the purpose of spreading local variability equally over all treatments. Furthermore, soil and stand characteristics were very homogeneous, which may support the original assumption of a very limited local variability. Concerning weather at the time of harvest, this factor was controlled by choosing operations that were conducted during the same season, and by expanding the number of study plots over a wide area that would take many weeks to harvest. However, it should be taken into consideration that our definition of »recovery« is based on this assumption, and not on a long term study that recorded soil characteristics in the same plots, over the years.

Furthermore, this study differs from most soil compaction studies (e.g. Sakai et al. 2008, Gerasimov and Katarov 2010, Majnounian and Jourgholami 2013) for its choice of a diffused sampling design. Other studies often adopt a localized sampling design, where paired samples are collected inside and outside machine tracks. However, these studies offer a very limited picture of the overall impact, unless they quantify the proportion of the total area covered by the tracks. Obtaining such information is especially difficult when sampling older cuts, where tracks have been cancelled by weather and re growth. In that case, there is a risk of sampling only the most severe examples of soil disturbance (i.e. those that are still visible after years) while missing lightly affected areas. As a result, these studies (e.g. Sakai et al. 2008, Gerasimov and Katarov 2010, Majnounian and Jourgholami 2013) may overestimate damage severity while underestimating the affected area. Furthermore, in the specific case of our study, operators did not follow a regular traffic pattern, which would have made it extremely difficult to estimate the total surface covered by tracks, if these were at all visible after 6 years. In fact, tracks were not visible in the 2011 plots, either. Therefore, we could not go for a paired sampling design, where samples would be collected separately inside and outside the ruts. Therefore, diffused random sampling was the only available option. In general, diffused sampling is a sensible choice whenever older plots need to be sampled, unless researchers have clearly marked the position of the tracks at the time of harvesting – years earlier. It should be taken into consideration that our study presents an average level of compaction, derived from sampling both trafficked and non-trafficked soil. That may lead to underestimating the actual compaction in the tracks. In contrast, conventional localized sampling as applied in other studies (e.g. Sakai et al. 2008, Gerasimov and Katarov 2010, Majnounian and Jourgholami 2013) tends to overestimate the average compaction level of the site. Since we adopted the same sampling design for all three treatments on test, the value of our comparison remains unbiased, whereas comparisons with previous studies should be interpreted with caution.

This said, the results of this study are consistent with those of other studies conducted in the same area, although under different silvicultural and technological conditions. In their study about mechanized thinning of pine plantations, Magagnotti et al. (2012) reported that the average bulk density of the forest soil was 1.2 g cm^{-3} and 1.3 g cm^{-3}, respectively, before and after harvesting. Slightly lower figures were obtained from windthrow salvage operations in the Park, where pre harvest bulk density was about 1 g cm^{-3} and post-harvest bulk density ranged from 1.1 to 1.2 g cm^{-3} (Spinelli et al. 2013).

In general, the post-harvest bulk density increases recorded in the Park are lower than reported for Central Europe and North America (Froehlich et al. 1986, Ampoorter et al. 2010), where they often range between 15 and 30% of the original pre harvest-values. This difference is likely explained by the resistance of sandy soils to compaction (Wästerlund 1985) and by the different sampling design.

High CO_2 concentration is a good indicator of reduced soil conductivity (Ponder 2005), which is a common consequence of compaction (Schack-Kirchner et al. 2001). Compaction decreases soil porosity, especially for what concerns pores greater than 3 mm in diameter, which have the highest conductivity (Huang et al. 1996). When air exchange is restricted, the respiration of soil biota induces an increase of CO_2 concentration (Von Wilpert and Schäffer 2006). If gas conductivity is severely reduced, CO_2 levels may reach very high concentrations that will restrict further breathing. In that case, soil productivity is curtailed, and so is the ability for biological recovery (Dick et al. 1988). Previous studies have shown that biological recovery is expected when CO_2 concentration is below 10 000 ppm: beyond this threshold, biological activity is so constrained that biological recovery will take a very long time. A CO_2 concentration above 20 000 ppm stalls almost all biological activity (Paul 2007): then recovery may only happen through physical agents, at times of prolonged drought or freezing (Magagnotti et al. 2012). CO_2 concentration in the soil air in the recently clear felled study plots was much lower than recorded after pine thinning in the same area (3 000 vs. 8 000 ppm), which may depend on a number of factors, including the different data collection method (Magagnotti et al. 2012). In the quoted study, CO_2 concentration readings were collected directly in the machine ruts, where compaction was highest. In this study, post-harvest readings were obtained by randomly sampling the whole clear cut area, so that our research averaged readings obtained inside and outside the ruts, which were invisible at the time of sampling.

One of the main assets of this study is in the concurrent use of different methods for gauging soil compaction. The agreement of all methods makes our conclusions especially robust. So we can safely state that the clear felling operations implemented in the park do result in measurable soil compaction, as witnessed by the concurrent increase of soil bulk density, soil penetration resistance, soil deflection and soil CO_2 concentration in the clear felled plots. However, the levels of compaction measured in this study are below critical values, which are estimated to 1.7 g cm^{-3} for bulk density (Heilman 1981), 3 to 6 MPa for penetration resistance (Lhotsky 2000, Whalley et al. 1995) and 7 000 to 10 000 ppm for CO_2 concentration (Magagnotti et al. 2012, Qi et al. 1994). The same accounts for soil porosity, which was significantly lower in clear felled plots, but still above the estimated 38% critical value (Lhotsky 2000). It indicates the resistance of sandy soil to compaction, even in case of operation of heavy machinery traffic. Furthermore, long term studies indicate that pine trees are resistant to the effect of soil compaction, which has little consequence on early (Lacey and Ryan 2000) and mature growth (Sanchez et al. 2006), which may justify cautious optimism.

What is more, this study suggests that recovery may already be visible six years after clear felling, especially for what concerns soil air conductivity. There was no significant difference in soil CO_2 concentration between plots clear felled in 2005 and plots that were not harvested at all. Similarly, penetration resistance was significantly lower in the 2005 plots, compared to recently clear felled plots. Of course, complete regeneration is not achieved within such a short period, as indicated by the permanence of alterations in bulk density, porosity and deflection characteristics. Yet, recovery seems well under way, and the vigorous brush regeneration that exploded right after clear fell may have an important role in loosening up the soil structure, especially in a Mediterranean climate where soil freezing is not a factor. Such a rapid soil recovery is in contrast with other studies, which report much longer regeneration times, in the order of 15 to 40 years (Ampoorter 2010, Von Wilpert and Schäffer 2006). Probably, recovery time is proportional to impact severity, which may be overestimated in traditional studies probing only inside the wheel tracks (Seybold et al. 1999).

A final and important remark must be made on the other causes of soil disturbance, besides mechanized clear-felling. It should be noted that we used the descriptive »non-harvested« instead of »undisturbed«. This choice is to acknowledge that areas that were not harvested did not necessarily represent pristine undisturbed sites. In the park there are many other sources of disturbance, including recreation, wildlife management and pine nut collection. Signs of these activities were especially visible in areas that were not harvested, while they had been cancelled in the clear felled areas. Furthermore, non-harvested areas may still bear the effects of previous thinning operations, if their impacts were particularly heavy and recovery incomplete. Therefore, our study quantified the additional impact of clear felling on areas that are already disturbed by a wide range of activities. Fortunately, the cumulative effect of these activities (including clear felling) does not seem to alter soil characteristics so much as to seriously threaten forest regeneration and further growth (Magagnotti et al. 2012).

6. Conclusions

Mechanized clear felling of mature umbrella pine plantation produces significant alterations of soil physical characteristics, additional to those eventually caused by other management activities. However, the extent of these alterations may not exceed critical limits, partly due to the resistance of sandy soil to compaction. What is more, recovery seems to be relatively fast. Six years after clear felling, CO_2 concentration is similar to that recorded in non-harvested plots, possibly indicating a recovery of soil conductivity, which is likely to accelerate the further restoration of original soil characteristics. These results may support the introduction of mechanized harvesting to coastal pine plantations established on sand dunes, which seem especially resilient to soil compaction.

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