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# Soil Disturbance Induced by Silvicultural Treatment in Chestnut (*Castanea sativa* Mill.) Coppice and Post-Disturbance Recovery

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**Abstract:** Chestnut forests represent an important environmental and landscape element in Europe, especially in the hill regions of southern Europe. In Italy, the total surface amount of chestnut forests is slightly expanded with 788,408 hectares, but orchards show a dramatic reduction (147,586 hectares or 20% of the total) and timber-producing stands a comparable expansion (605,888 hectares or 80%). The coppice management actually applied is considered one of the oldest forms of sustainable forest management. Over the years, coppice highlighted its versatility, resilience and multifunctionality. In this management system, in consideration of the "frequent" cutting cycles, special attention must be paid to forestry operations, because tree damage and soil compaction can trigger fungal disease and soil erosion. Frequent and repeated machine traffic increases the risk for soil degradation derived from compaction, topsoil removal and general disturbance. This study covered different forest areas and mechanization levels, in order to evaluate if the extent, type and severity of soil disturbance changed with site characteristics and logging technique. Furthermore, the study sought to obtain a better knowledge about the recovery time required for restoring the original soil properties after a disturbance has occurred. The findings showed that physical, chemical, and biological soil features were only partially disturbed by the coppicing and again that a high level of specialized mechanization does not generate heavier soil impact compared with the smaller and lighter machines deployed under the traditional and intermediate mechanization scenarios. Soil recovery in the impacted areas is already measurable one year after harvest and may be complete within the eight year—that is halfway through the standard rotation applied in the region to chestnut coppice.

**Keywords:** chestnut coppice; logging operation; soil impact; soil biological quality; QBS-ar

## 1. Introduction

Sweet chestnut (*Castanea sativa* Miller) forests represent an important environmental and landscape element in Europe, especially in the hill regions of southern Europe [1,2]. In Italy, chestnut forest management has undergone important changes in the last 100 years. Right after the second World War, the Italian official statistics recorded 447,000 hectares of nut-producing chestnut orchards (62%) and 275,186 hectares of timber-producing chestnut coppice (38%). Following the radical economic, social and ecological changes of the post-war years, most of the orchards were coppiced and turned to timber production. Presently, the total surface amount of chestnut forests is slightly expanded with

788,408 hectares, but orchards show a dramatic reduction (147,586 hectares or 20% of the total) and timber-producing stands a comparable expansion (605,888 hectares or 80%) [3].

In the Mediterranean region there are over 23 million hectares of coppice forests, which are considered one of the oldest forms of sustainable forest management [4]. Over the years, this management system has proven its versatility and resistance, combined with an important multifunctionality [5–9]. A large proportion of the Italian forests are coppice stands (41.8% of total forests), mostly represented by the "coppice with standards" typology [3].

In particular, Chestnut coppice is the result of a silvicultural system that has lasted for centuries and it does guarantee continuity and stability to the forest cover. Chestnut coppice has an important role in Italian forestry, not only for the wide range of wood products it offers, but also for the widespread presence on the Italian territory: as a matter of fact, chestnut coppice is found from the Alps to Sicily over large areas as the result of its intense cultivation for many centuries.

As a species, chestnut offers many advantages, such as rapidity growth, good timber quality and high pollination capacity [10]. On the other hand, the species also has some weakness, such as its high susceptibility to pathogens and the tendency to ring shake in some regions. Generally, these limiting factors are linked to the type of management and possibly to the logging methods applied during harvesting [11,12]. In any case, the report attached to the National Forest Inventory [3] states that the overall health of the Italian chestnut forests is critical, since only 29% of the surveyed stands were free from any type of damage. In particular, chestnut has been badly hit by two fungal diseases: Bark canker caused by *Cryphonectria parasitica* and ink disease caused by *Phytophthora cambivora* [13]. In recent years extensive damage has also been caused by exotic insects, such as the *Dryocosmus kuriphilus* Yasumatsu, commonly known as the 'chestnut gall wasp' [14].

That makes the implementation of sustainable forest management especially appropriate when dealing with chestnut coppice [15]. Special attention must be paid to forestry operations, because tree damage and soil compaction can trigger fungal disease and the potential for damage is particularly high in coppice forests that are managed according to short rotations and undergo management operations more frequently than other forest types [16,17]. Frequent and repeated machine traffic increases the risk for soil degradation derived from compaction, topsoil removal and general disturbance [18–21].

The most recent findings on the coppicing of Mediterranean forests [8,9,15,22] suggest that operation has measurable impacts on the forest soil and regeneration, but recovery is also quite fast: Marchi et al. [8] and Venanzi et al. [9,22] assessed the impact of silvicultural treatment and harvesting operations on the regeneration composition and soil characteristics of oak coppice forests for a period of 6 years after harvesting, and their findings indicated that regeneration was not affected by the silvicultural treatment or the harvesting operation, while the physical, chemical, and biological features of the soil were, but recovery to the original parameters was almost complete within the sixth year after harvest.

Venanzi et al. [15] also assessed the soil impact associated with the final harvesting of a chestnut coppice with standards, for a period of 0–2 years after harvesting, and found that the physical, chemical and biological soil characteristics were only partially affected by the silvicultural treatment "per se", but they were strongly impacted by the harvesting operation and the recovery trend was not clear. Furthermore, the type and severity of these impacts changed depending on logging technique and technology. It is important however to understand how the magnitude of the impacts are affected by site characteristics, silvicultural management and climatic condition [17,23].

The assessment of ground disturbance and the mitigation of any possible damage could be considered one of the main focus of Sustainable Forest Management (SFM) [24–26] and Sustainable Forest Operations (SFO) [27],since carefully managed forest ecosystems are highly resilient in the medium-long-term [24–26,28].

The present study was designed to analyze the soil disturbance caused by the silvicultural treatment and the logging operation, with special focus on chestnut coppice. Following validated research protocols, researchers determined the physical (bulk density, penetration resistance and shear resistance), chemical (pH, organic matter) and biological (arthropod activity—QBS-ar) characteristics of the forest soil before and after harvesting [15,29,30]. The study covered different forest areas and mechanization levels, in order to evaluate if the extent, type, and severity of soil disturbance changed with site characteristics and logging technique. Furthermore, the study sought to obtain a better knowledge about the recovery time required for restoring the original soil properties after a disturbance has occurred.

This study was an extension of a previous research conducted on other stand types [15] and had the following objectives:

(i) To determine the impact of silvicultural treatment (i.e., cover removal) on soil conditions;
(ii) to determine and the impact of the forest operation (i.e., traffic) on soil characteristics;
(iii) to compare the impact type and severity associated with different types of logging technology (i.e., mechanization level); and
(iv) to estimate the recovery capacity of soil after disturbance.

## 2. Materials and Methods

### 2.1. Study Sites

The study was conducted in two chestnut (*Castanea sativa* Mill.) coppice stands: One on the Cimini Mountain (42°36′92.16′′ N, 12°20′28.00′′ E) near Viterbo, and the other on the Amiata Mountain (42°52′06.50′′ N, 11°40′10.02′′ E) near Abbadia S. Salvatore (Siena), both in Central Italy.

The Cimini forest stand was a coppice with standards and covered 10 ha. It was located at an elevation of 590 m a.s.l., on a slope with an average gradient of 45%. Ground surface was uneven, with about 10% of the surface showing obstacles to machine traffic, such as rock outcrops and hollows. The climate was Mediterranean, characterized by hot summers and mild-rainy autumns and early springs. Mean annual precipitation was about 900 mm and mean annual temperature was 14.8 °C. The highest daily temperatures were recorded in July or August (31 °C, average maximum) and the lowest in January (1 °C, average minimum). The study compartment was served by two forest roads but had no skid trails. One forest road divided the forest into two parcels and intersected the other road that served both parcels. The soil was generally deep and remarkably permeable, which favored infiltration, percolation and internal circulation, as well as the rapid decomposition of litter that created a mull type humus [31]. The soil classification in the area was non-hydromorph brown soil, acidic reaction or sub-acidic [31].

The Amiata forest stand was also a coppice with standards and covered 20 ha. It was located at an elevation of 850 m a.s.l., on a slope with an average gradient of 38%. Ground surface was uneven, with about 7% of the surface showing obstacles to machine traffic, such as rock outcrops and hollows. The climate was cold-tempered, characterized by cool summers, and rainy autumns and late springs. Mean annual precipitation was about 950 mm and mean annual temperature was 12 °C. The highest daily temperatures were recorded in July or August (27 °C, average maximum) and the lowest in January (−3 °C, average minimum). The study compartment was served by two forest roads and two skid trails. The soil was generally deep, developing from volcanites on clayey and marly lithotypes with arenaceous intercalations. This considerably affected soil texture and structure, which were quite particular. The volcanic soils of Monte Amiata are known for being very favorable to chestnut and most such stands are included within the highest fertility classes; however, these soils are very sensitive to erosion and therefore special caution is needed both in the use of coppice and in the cultivation of chestnut trees [32].

### 2.2. Treatment and Logging Methods

The study forests were managed as coppice with standards, which is the most common coppice management system in Italy, since it can guarantee good profit for the owner and continuous partial canopy cover. The yield of chestnut coppice in the study regions was high and wood quality quite good.

The study stands were harvested on 16 year rotations. The treatment consisted in the almost complete removal of the trees, releasing 60 standards per hectare. The harvesting operation was done mainly during the winter season and was completed in about 100 days. The tree length system (TLS) was applied in most cases, and in the study stands too. Pre-harvest stand data were obtained with standard mensuration techniques on eight randomly selected circular sample plots for every harvested area. Plot surface area was 314 $m^2$. Stand characteristics are shown in Table 1.

**Table 1.** Pre-harvest (TML, AML, IML) and controls plots (C1, C2) dendrometric characteristics. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level; C1: control area for TML; C2: control area for IML and AML.

| Area | Age [year] | | DBH * [cm] | | Height * [m] | | Density * [trees/ha] | Basal Area [$m^2$/ha] | Above- Ground Biomass Stock [$m^3$/ha] | Above- Ground Biomass Harvested [$m^3$/ha] |
|---|---|---|---|---|---|---|---|---|---|---|
| | Shoots | Standards | Shoots | Standards | Shoots | Standards | | | | |
| TML | 16 | 35 | 16.0 ± 3.1 | 26.3 ± 2.5 | 12.4 ± 1.0 | 15.6 ± 1.2 | 1250 ± 57 | 26.7 | 187.3 | 172.5 |
| IML | 16 | 55 | 11.9 ± 1.8 | 31.1 ± 4.2 | 15.1 ± 1.2 | 16.8 ± 1.5 | 1920 ± 81 | 22.1 | 165.2 | 150.2 |
| AML | 16 | 54 | 12.2 ± 2.1 | 29.8 ± 3.8 | 14.9 ± 2.0 | 17.9 ± 1.0 | 1850 ± 29 | 22.7 | 157.1 | 142.1 |
| C1 | 16 | 39 | 15.9 ± 7.2 | 26.5 ± 6.2 | 12.5 ± 1.7 | 15.9 ± 1.7 | 1242 ± 30 | 26.1 | 182.1 | - |
| C2 | 16 | 56 | 12.5 ± 4.1 | 31.1 ± 1.2 | 16.8 ± 1.1 | 18.8 ± 2.1 | 1595 ± 81 | 20.5 | 181.7 | - |

* (average ± SD).

The logging system tree-length in all cases, and it always aimed at the main production of structural timber, but three different mechanization levels were introduced: Traditional (TML), intermediate (IML) and advanced (AML).

Three mechanization levels were included in the investigation:

1. Cimini forest, Traditional Mechanization Level, Area TML (about 10 ha);
2. Amiata forest, Intermediate Mechanization Level, Area IML (about 10 ha); and
3. Amiata forest, Advanced Mechanization Level, Area AML (about 10 ha).

Two control plots were selected:

1. Cimini forest, Area C1 (about 10 ha)—unharvested and not impacted for more than 16 years, near the TML area;
2. Amiata forest, Area C2 (about 10 ha)—unharvested and not impacted for more than 16 years, near the IML and AML areas.

In the Cimino forest, all trees were felled and delimbed motor-manually with a Stihl MS 260 chainsaw. Bunching and extraction was performed with a four-wheel drive farm tractor (Lamborghini 79 kW, weight 4.3 t), equipped with a bolt-on hydraulic winch with a maximum pull force of 40 kN and a logging arch [33]. Due to the absence of skid trails, the tractor travelled directly on the forest floor to reach the trees to be extracted. Occasionally, timber was pulled directly from the forest road using the winch. The average load size was 3.2 t.

In the Amiata forest and under the intermediate mechanization level treatment, all trees were felled and delimbed motor-manually with a Stihl MS 260 chainsaw. Bunching and extraction was performed with a four-wheel drive farm tractor (Same 85 kW, weight 4.6 t), equipped with a forest winch with a maximum pull force of 60 kN. The tractor travelled on the skid-trails and pulled the trees to them using its winch: then, loads were skidded to the landing. During the surveys the average load size per trip was 2.69 t.

In the Amiata forest and under the advanced mechanization level treatment, all trees were felled and delimbed with a harvester (Timberjack 1270 C harvester, 150 kW, with a TBJ 762 C head with total mass of 19 t). Extraction was performed with a forwarder (John Deere 1410D eco III eight-wheeled, 136 kW, an empty weight of 16.6 t and payload capacity of 14 t). Forwarding operations were synthetized as follow: travel on the road, when the forwarder ran on the forest road; travel on the forest floor, when the forwarder left the forest road and entered the stand; pick up of the logs, the forwarder picking the logs with its 7.5 m hydraulic loader; finally once a full load had been assembled, the forwarder drove back to the forest road and then to the landing. The average load recorded was 11.65 t.

In fact, the slope gradient recorded in all sites was close to the limit for the use of ground-based equipment [34]: yet, Italian loggers often push their equipment close to its mobility limits, as already shown in recent studies that provide good witness to the use of forestry equipment on slopes close to 50% [35]. Farm tractors do not have such a good mobility as purpose-built forestry machines, but both tractors used in the study were equipped with a winch and they actually travelled only on the gentler areas, reaching trees laying on the steepest one using their winch [36]. In any case, the technologies covered in this study are among the most common used for harvesting coppice stands across most of Europe [37].

### 2.3. Analytical Methods

Soil disturbance was assessed on six randomly selected sample plots for each harvested forest area and for each control (TML, IML, AML, C1 and C2) for a total of 30 sample plots. For the sample plots in the harvested areas, two different strata were selected based on a visual assessment for the evidence of disturbance (e.g., the presence or absence of bent understory, crushed litter, ruts or soil mixing). Conversely, for the sample plots in the two control areas only one stratum was considered (e.g., no visual evidence of disturbance).

In order to determine the soil physical and chemical characteristics, researchers determined soil texture, bulk density (BD), penetration resistance (PR), shear resistance (SR), organic matter (OM) and pH in each plot and stratum.

Soil texture was assessed analyzing three soil samples for plot and stratum as detailed by Marchi et al. [8] and Venanzi et al. [9].

In order to find the soil classes using the textural USDA triangle [38], silt, clay, and sand were determined using the Andreasen pipette method [39].

For BD, PR, and SR, measurements were conducted according to the systems described in Marchi et al. [8] and reported in Mg $m^{-3}$, MPa and t $m^{-2}$, respectively.

The pH value and OM were measured as described in Venanzi et al. [9] and Venanzi et al. [22] respectively.

Post-operation analyses were made in order to evaluate the proportion of the total plot surface impacted by the operation (machine traffic, wood dragging on the soil etc.) by impact type and severity. For this purpose, a systematic sampling method was applied in each area, using 1 m × 50 m grid traced with a compass and a tape measure. At each intersection in the grid, researchers produced a visual assessment of disturbance type and severity.

Furthermore, disturbance and recovery were also assessed by determining biological activity in the soil system, reported in terms of the QBS-ar index. This index is calculated based on the presence and activity of micro-arthropod population and it has shown to be an extremely sensitive indicator of environmental variations caused by human disturbance. This index is mainly qualitative and evaluates the presence and complexity of the soil microarthropod population. The methodology applied was reported in Venanzi et al. [15] and Marchi et al. [8].

These post harvesting measurements and assessment of soil characteristics were repeated every year for 6 years, starting from the completion of the logging activities. Measurements were collected in the same month, during the early summer, in order to operate consistently under similar weather conditions.

### 2.4. Statistics

Using Statistica 7.1 (2007) software, data distribution was plotted and checked for normality and homogeneity of variance through the Lilliefors and Levene tests. *t*-test, ANOVA or MANOVA were used to check the statistical significance of eventual differences between treatments. The Tukey HSD test was used to pinpoint differences on specific treatments. Data that violated the parametric assumptions (i.e., normal distribution and homogeneity of variance) were analyzed with non-parametric techniques, such as the Kruskal–Wallis test.

Non-Metric Multidimensional Scaling (NMDS) was used to show the differences in the average soil parameters for the different treatments.

## 3. Results and Discussion

### *3.1. Proportion of the Impacted Surface*

Visual inspection found that some form of disturbance affected between 27% and 35% of the total surface area. The proportion of visible disturbance changed with treatment and it was significantly lower for TML compared with AML. The IML treatment was in between and in that case the proportion of disturbed surface did not differ significantly from either of the other treatments. These figures are consistent with those found for ground-based logging in other studies conducted in Italy on the same type of forests and operations [9,22,33,40,41], but notably lower to those obtained in those studies covering much denser stands [36,42].

In general, the surface visibly disturbed by forest operations is variable ranging from <5% to >50%: In that regard, the type of silvicultural intervention seems to have a stronger influence than the harvesting technique [22,43,44], considering that the main discriminating factors of these forest yards mentioned are the type of silvicultural intervention (Table 2).

**Table 2.** Soil area impacted by bunching and extraction activities (ANOVA results; average ± SD). TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level.

| Area | *p*-Value | Disturbed Soil | Undisturbed Soil |
|---|---|---|---|
| TML | <0.05 | 26.9 ± 2.6% [a] | 73.1% |
| IML | | 29.6 ± 6.6% [a,b] | 70.4% |
| AML | | 34.6 ± 3.3% [b,c] | 65.4% |

Note: Different letters after means within each mechanization level indicate significant differences by Tukey test ($p < 0.05$).

### *3.2. Soil Physical and Chemical Characteristics*

Soil texture was similar in all three plots and was characterized by a dominant proportion of sand particles, always in the vicinity of 60% of total dry weight. The second most important particle size class was silt, which accounted for 36% of total weight in the TML area and 30% in the other two areas. Clay represented the balance and accounted for 4% in the TML area and 10% in the others. Obviously, the same accounted for the control plots that were adjacent to the study areas. As a result, the soil in the three study areas and the respective controls was defined as a sandy-loam, moisture field capacity (CC) was estimated with the Soil Water method at 21%.

Soil moisture during all sampling periods was in the 50% to 60% range, without any statistically significant differences between treatments.

The situation for soil bulk density (BD) was more complex: No significant differences were found between BD in the control areas and in the undisturbed strata of the harvested areas under the IML and AML treatments, regardless of time after harvesting (1 to 6 years). Conversely, under the TML treatment, soil BD was significantly higher in the plots located in the undisturbed stratum within the harvest areas, compared with the control. This difference decreased with time and was highest one years after harvesting (39%) but was still large (20%) and significant even six year after harvesting. Since bulk density was higher in areas that experienced the removal of canopy cover but suffered no traffic, it is surmised that the increase in bulk density was caused by the action of weather events, in particular the impact of precipitation that hit the soil directly wherever canopy cover is absent [15].

Further comparisons were conducted between the untrafficked and trafficked strata within the harvested areas in order to remove the effect of canopy cover removal and isolate that of direct machine traffic. One year after harvesting the bulk density in the trafficked strata was approximately 10% higher than in the untrafficked strata under the TML and IML treatments (Figure 1). This is considered to be mainly caused by the compacting action of load transportation and vehicles. Similar values have been observed in other studies where not only loads but vehicles moved on the forest soil [36,45]. In contrast, no such increase was found under the AML treatment, possibly due to the different extraction mode (forwarding vs. winching and skidding) and to the low ground pressure exerted by the forwarder wheels, especially when fitted with bogie tracks.

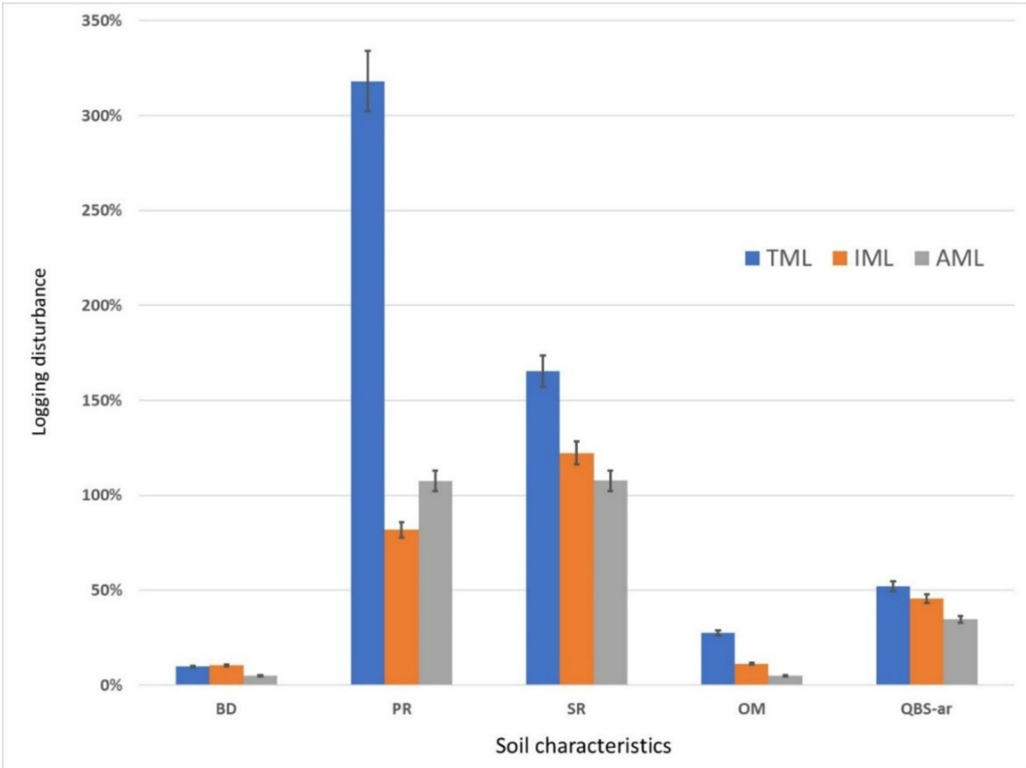


**Figure 1.** Graphical interpretation of the logging disturbance on soil characteristics, one year after harvesting. BD: bulk density; PR: penetration resistance; SR: shear resistance; OM: organic matter content; QBS-ar: soil biological quality index referred to microarthropod. TML: traditional mechanization level; IML: intermediate mechanization level; HML: advanced mechanization level.

Six years after harvesting bulk density values had decreased in all cases, and differences between the trafficked and untrafficked strata remained only significant for the IML treatment (Figure 2), while soil bulk density in the area under the TML treatment had returned to untrafficked values.

These results are consistent with those found in previous studies. The 10% BD increase recorded matches with the 12% increase recorded by Kleibl et al. [46] in Mediterranean pine forests, while it differs slightly from 14–19% increase found by Venanzi et al. [22]. This value is twice as large as found by Magagnotti et al. [47] for skidders (increase in soil BD ca. 6%), but one must account for the different technology and for the very good floatation capacity of the dedicated forest equipment used in Magagnotti et al. [47] and this follows the result found in AML area.

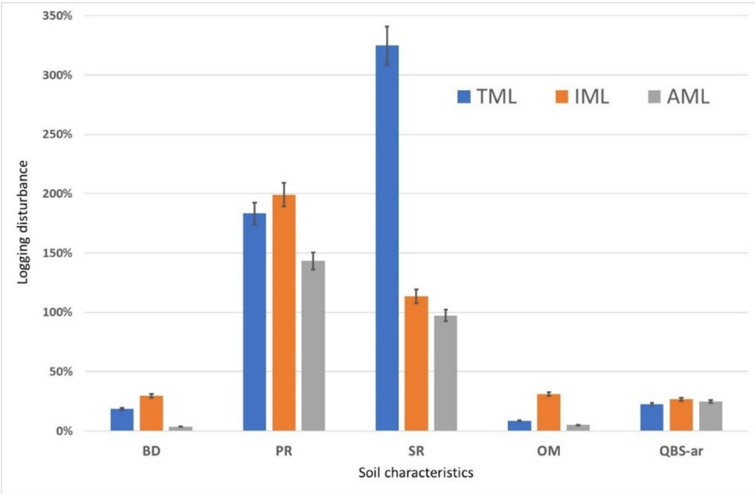


**Figure 2.** Graphical interpretation of the logging disturbance on soil characteristics, six years after harvesting. BD: bulk density; PR: penetration resistance; SR: shear resistance; OM: organic matter content; QBS-ar: soil biological quality index referred to microarthropod. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level.

However, the soil BD values found in previous studies and those recorded in the present study are almost the same, and range between 0.7 and 1.3 g $cm^{-3}$. Considering that different authors suggest that root growth is impaired only when soil BD ranging of 1.7 to 1.8 g $cm^{-3}$ and over [26,48,49], our results appear very important. Therefore, it is impossible that the compaction recorded in this study may stop forest growth, which is also confirmed by the fast soil recovery rate showed (Figures 3 and 4). This agrees with the findings of a similar study [22] where the original soil properties were fully restored within 6 years.

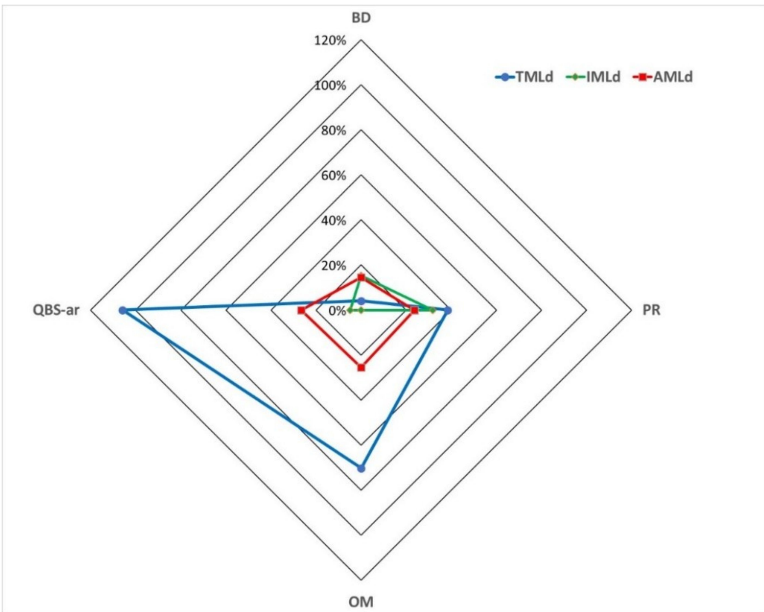


**Figure 3.** Graphical interpretation of the percentage of soil characteristics recovery, six years after harvesting, specifically referred to the disturbed strata (d). BD: bulk density; PR: penetration resistance; OM: organic matter content; QBS-ar: soil biological quality index referred to microarthropod. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level.

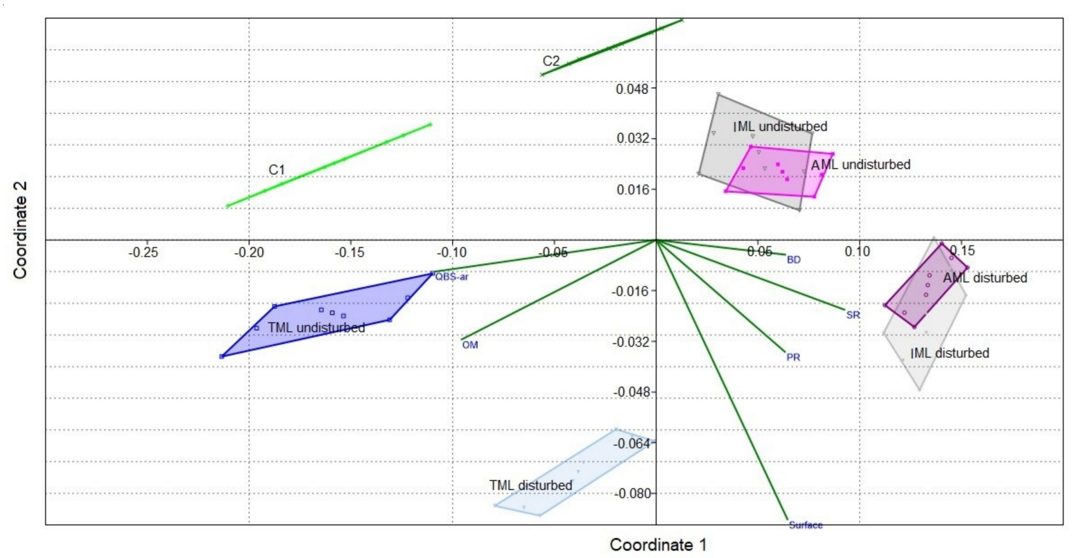


**Figure 4.** Assessment of the main logging impact indexes and indicators referred to soil (BD bulk density; PR: penetration resistance; SR: shear resistance; OM: organic matter content; QBS-ar: QBS-ar index) by nMDS analysis. Difference tested between the three mechanization levels and the control areas six years post harvesting. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level; C1: control area for TML; C2: control area for IML and AML.

The results of soil penetration resistance (PR) and shear resistance (SR) tests matched the same trends disclosed by the bulk density tests and showed statistically significant differences between the three mechanization levels, the two soil strata (disturbed and undisturbed) and the two period (one and six years after harvest). However, neither PR nor SR were affected by canopy cover removal alone (Table 3), which is consistent with the findings of previous studies [9]. One year after harvest, PR and SR were at least twice as high in the trafficked strata as in the untrafficked ones, regardless of treatment (Table 3). Six years after harvest, PR and SR in the trafficked strata had decreased substantially, but they were still significantly higher than recorded in the untrafficked strata, indicating that recovery was not complete yet (Figure 4).

**Table 3.** Results of the ANOVA and Tukey test for BD, penetration and shear resistance (average ± SD), difference tested among disturbed, undisturbed and control soil, for the three mechanization levels. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level; C1: control area for TML; C2: control area for IML and AML.

| Area | Soil Type | Bulk Density [g/cm$^3$] | | Penetration Resistance [MPa] | | Shear Resistance [t/m$^2$] | |
|---|---|---|---|---|---|---|---|
| | | 1 Year | 6 Year | 1 Year | 6 Year | 1 Year | 6 Year |
| TML | Und | 0.747 ± 0.150 $^a$ | 0.664 ± 0.079 $^a$ | 0.066 ± 0.011 $^a$ | 0.060 ± 0.012 $^a$ | 1.550 ± 0.272 $^a$ | 1.110 ± 0.109 $^a$ |
| | Dis | 0.820 ± 0.210 $^b$ | 0.787 ± 0.077 $^a$ | 0.276 ± 0.090 $^b$ | 0.170 ± 0.081 $^c$ | 4.113 ± 0.591 $^b$ | 4.715 ± 0.318 $^b$ |
| C1 | Contr | 0.537 ± 0.110 $^c$ | 0.552 ± 0.091 $^c$ | 0.069 ± 0.012 $^a$ | 0.058 ± 0.010 $^a$ | 1.569 ± 0.310 $^a$ | 1.687 ± 0.151 $^a$ |
| IML | Und | 1.070 ± 0.098 $^d$ | 0.772 ± 0.114 $^a$ | 0.292 ± 0.074 $^b$ | 0.121 ± 0.062 $^d$ | 3.633 ± 0.204 $^b$ | 4.624 ± 0.114 $^b$ |
| | Dis | 1.182 ± 0.110 $^b$ | 1.001 ± 0.092 $^d$ | 0.531 ± 0.098 $^c$ | 0.362 ± 0.074 $^e$ | 8.077 ± 0.079 $^c$ | 9.873 ± 0.117 $^c$ |
| C2 | Contr | 0.971 ± 0.092 $^d$ | 0.921 ± 0.120 $^b$ | 0.263 ± 0.084 $^b$ | 0.123 ± 0.095 $^d$ | 4.762 ± 0.125 $^b$ | 5.022 ± 0.120 $^b$ |
| AML | Und | 0.992 ± 0.109 $^d$ | 0.860 ± 0.099 $^b$ | 0.184 ± 0.092 $^d$ | 0.120 ± 0.110 $^d$ | 3.025 ± 0.119 $^b$ | 3.472 ± 0.119 $^b$ |
| | Dis | 1.041 ± 0.111 $^d$ | 0.891 ± 0.121 $^b$ | 0.382 ± 0.091 $^e$ | 0.292 ± 0.081 $^b$ | 6.284 ± 0.122 $^d$ | 6.848 ± 0.089 $^d$ |
| C2 | Contr | 0.971 ± 0.092 $^d$ | 0.921 ± 0.120 $^b$ | 0.263 ± 0.084 $^b$ | 0.123 ± 0.095 $^d$ | 4.762 ± 0.125 $^b$ | 5.022 ± 0.120 $^b$ |

Note: Different letters after means within each mechanization level indicate significant differences by Tukey test ($p < 0.05$).

The organic matter (OM) content in the soil did not change significantly between the untrafficked strata in the harvested areas and the control areas, indicating that the removal of canopy cover would not result in a significant change of soil OM content (Table 4). Harvesting impacted OM content only under the TML treatment and only one year after harvest—untrafficked levels being fully restored at the end of the observation period (i.e, six years after harvest). Differences between treatments were significant, but that was true for trafficked, untrafficked and control plots, indicating a location bias—that is an original difference in soil OM content between the Cimini and Amiata sites. The decrease in OM (5%) in the disturbed soil can be linked to the decrease in mineralization due to the decrease of microbial activity in the disturbed area [50]. The fact that this was only observed under the TML treatment in the Cimini site may depend on the fact that the Cimini site was the richest in OM content to start with, and therefore any changes were likely to be larger (hence more noticeable) there, compared with the Amiata site. In all cases, soil OM content was back to pre-harvest levels six years after harvesting.

**Table 4.** Results of the ANOVA and Tukey test for organic matter content and pH (average ± SD), difference tested among disturbed, undisturbed and control soil, for the three mechanization levels. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level; C1: control area for TML; C2: control area for IML and AML.

| Area | Soil Type | Organic Matter [%] | | pH | |
|---|---|---|---|---|---|
| | | 1 Year | 6 Year | 1 Year | 6 Year |
| TML | Und | 18.1 ± 1.3 $^{a}$ | 24.4 ± 1.1 $^{d}$ | 5.3 ± 1.0 | 5.2 ± 1.0 |
| | Dis | 13.1 ± 1.6 $^{b}$ | 22.3 ± 1.0 $^{d}$ | 5.2 ± 0.9 | 5.4 ± 0.9 |
| C1 | Contr | 19.2 ± 1.3 $^{a}$ | 26.7 ± 0.9 $^{d}$ | 5.2 ± 1.0 | 5.3 ± 1.1 |
| IML | Und | 6.2 ± 1.0 $^{c}$ | 7.4 ± 1.1 $^{c}$ | 4.5 ± 1.1 | 4.5 ± 1.1 |
| | Dis | 5.5 ± 1.1 $^{c}$ | 5.1 ± 1.1 $^{c}$ | 5.0 ± 0.8 | 4.8 ± 1.0 |
| C2 | Contr | 6.2 ± 1.2 $^{c}$ | 9.8 ± 0.8 $^{e}$ | 4.8 ± 1.1 | 4.9 ± 1.0 |
| AML | Und | 6.2 ± 1.0 $^{c}$ | 9.5 ± 1.2 $^{e}$ | 4.7 ± 1.0 | 4.7 ± 1.1 |
| | Dis | 6.3 ± 1.1 $^{c}$ | 7.9 ± 1.1 $^{c,e}$ | 5.0 ± 0.8 | 5.1 ± 0.8 |
| C2 | Contr | 6.2 ± 1.2 $^{c}$ | 9.8 ± 0.8 $^{e}$ | 4.8 ± 1.1 | 4.9 ± 1.0 |

Note: Different letters after means within each mechanization level indicate significant differences by Tukey test ($p < 0.05$).

Soil pH was not affected by either silvicultural treatment (i.e., removal of canopy cover) or harvesting (i.e., machine traffic—see Table 4). Perhaps, this is due to the general high level of soil acidity in the study areas, which would have been hard to further increase by silvicultural operations alone.

### *3.3. Soil Biodiversity Analysis*

The QBS-ar index (QBS-ar) showed statistically significant differences between the three mechanization levels, soil strata (trafficked and untrafficked) and periods (Table 5). The range of variation was quite large (from 83 to 271), consistently with what was observed in previous studies by Venanzi et al. [9,15,22] and Rüdisser et al. [51].

One year after harvesting, QBS-ar index values did not differ significantly between the control areas and the untrafficked strata within the corresponding harvest areas, indicating that the removal of canopy cover did not impact arthropod activity in the forest soil. In contrast, index values were about 20% smaller in the trafficked strata even six years after harvesting, indicating a decrease in the soil biological activity connected with direct machine traffic (Figure 3).

**Table 5.** Results of the Kruskall–Wallis and Tukey test for QBS-ar index, difference tested among disturbed, undisturbed and control soil, for the three mechanization levels. TML: Traditional mechanization level; IML: Intermediate mechanization level; AML: Advanced mechanization level; C1: control area for TML; C2: control area for IML and AML.

| Area | Soil Type | QBS-ar | | *p*-Value |
|---|---|---|---|---|
| | | 1 Year | 6 Year | |
| TML | Und | 213 [a] | 271 [e] | <0.05 |
| | Dis | 102 [b] | 210 [a] | |
| C1 | Contr | 198 [a] | 263 [e] | |
| IML | Und | 187 [a] | 146 [f] | <0.05 |
| | Dis | 102 [b] | 107 [b] | |
| C2 | Contr | 126 [c] | 181 [a] | |
| AML | Und | 127 [c] | 140 [f] | <0.05 |
| | Dis | 83 [d] | 105 [b] | |
| C2 | Contr | 126 [c] | 181 [a] | |

Note: Different letters after means within each mechanization level indicate significant differences by Tukey test ($p < 0.05$).

After accounting for the site differences between the Cimini and the Amiata sites, it appears that the impact on soil biological activity was lowest for the AML treatment. That may be related to the different extraction technique (i.e., forwarding instead of skidding) and to the lower ground pressure of the larger dedicated machine compared with the smaller but adapted tractors: The former is propelled by eight wide wheels through a smoother hydrostatic transmission, while the latter use only four narrower wheels with aggressive tire lugs. It is also likely that the higher productivity recorded under the AML treatment and the consequently shorter residence time of the operation contributed to mitigate the impact on soil microfauna, which was disturbed for a short time only and could resume its soil colonization activity much sooner than under all other treatments [22,36,45].

### 3.4. NMDS Scaling

Principal Non-Metric Multidimensional Scaling (NMDS) tests produced a two-dimensional ranking (Figure 4) that provided a significantly greater reduction in statistical stress than expected by chance ($\alpha = 0.05$). The two axes in the graph could explain 98% of the overall variance in the values for the proportion of visually disturbed surface area, BD, PR, SR, OM, and QBS-ar index. These six variables showed the maximum correlation with the ordination axes. The variables proportion of visually disturbed surface area, PR, SR, and OM illustrated the soil scenario on the weighted scale of axis 1 (Figure 4). The impact arrangement along axis 2 was dominated mainly by QBS-ar index and in part by BD (Figure 4).

Six years after harvesting, soil characteristics in the trafficked strata were still significantly different than recorded in the untrafficked strata, in contrast with what was found by Venanzi et al. [22] for different soil and stand types within the same region. Areas under the TML treatment area showed the best recovery rates (Figure 4), but even here recovery was not complete because some soil characteristics (PR and SR) were still significantly different from those found in the corresponding untrafficked areas. Recovery was even less complete under the IML and AML treatments (Figure 4).

The differences between the results of this study and of those previously conducted on the same subject by the same Authors [9], are likely due to the different soil and climate conditions, and also to a more intensive management of the chestnut coppice stands. In Venanzi et al. [9] the recovery of soil impacts caused by coppicing was almost complete 3 years after harvesting, and the trend was such the full recovery would expect by the fifth year. On the other, another study by the same Author in again a different stand type indicated that full recovery may not occur earlier than 8 to 9 years after harvesting [22], which would be consistent with the result of the present experiment. Therefore, one may surmise that recovery rates are associated with stand and soil type, not just harvesting technique and/or technology. In any case, all studies emerged clear evidence of recovery, which may be occurring at relatively fast rates—although different from case to case.

### *3.5. Study Limitations*

Finally, it is important to state upfront the limitations of this study so that any conclusions are interpreted with due caution, especially when it comes to generalization. In particular, this study has two main limitations, and namely: The testing of specific applications of wider general harvesting techniques and the comparison being conducted in different locations, not on the same one. Concerning the former, the question is that any of the mechanization levels under test could be represented by a number of different harvesting techniques and equipment types. For instance, advanced mechanization could be applied through a feller-buncher a skidder and a processor, or through a harvester and a forwarder—as in our case. Even when a harvester and a forwarder were applied, there are many types, sizes and models one can choose from. Therefore, the three operations selected in this study to represent the corresponding three mechanization levels are just samples from a very wide and diversified universe. Based on that, the results of this study only allow making a very detailed statement of what is verified and a very general statement of what is not. More precisely, one can state that the specific operations in this study produced the impacts reported here under the specific conditions of the study. This is good knowledge, although poorly suited to generalization and can be used to estimate the expected soil impact that may occur under different conditions with much approximation only. Therefore, the production of general knowledge will require more studies on the same type that may cover the most common alternative conditions that this study had to exclude due to resource limitations. On the other hand, this study does offer an even more valuable general piece of knowledge, by dispelling the commonly held opinion that the larger and heavier machines that support advanced mechanization generate heavier soil impact compared with the smaller and lighter machines deployed under the traditional and intermediate mechanization scenarios [43]. This is indeed a very important contribution to current knowledge on the subject, and something that must be considered in all future debates on the relationship between harvesting technology and site impact. It is the quality of the soil–machine interface that determines impact potential—not just machine weight [52].

Concerning the second limitation—namely the use of different sites for the comparison—one cannot deny that a side-by-side comparison conducted on the same plot and under a more rigorous experimental plan (e.g., split-plot) would have offer better accuracy and a superior guarantee of reliability for the results eventually obtained from the experiment. However, organizing such a comparison would require unusually favorable circumstances, and a larger availability of resources than were actually made available to the research team. Hence the decision to fall back on a largely observational experimental design, which was duly corrected by selecting sites that were very similar between them in all respects, including soil type, stand type, silviculture, climate and operational conditions. Furthermore, selection of separate sites may have somewhat weakened the between-sites technology comparison but had no negative effects on the within-site impact assessment, since the untrafficked sample plots and the control plots were all located within sites. Therefore, the multi-site experimental design was not a limitation when it came to determine local impact levels and impact recovery rates.

## 4. Conclusions

Soil recovery in the impacted areas is already measurable one year after harvest and may be complete within the eight year—that is halfway through the standard rotation applied in the region to chestnut coppice. Such knowledge represents a crucial element in support of coppice management, since it relieves concern about the cumulation of impacts due to the very short rotations normally applied to these stands. Together with the fact that advanced mechanization may not actually cause any larger soil impacts than traditional mechanization (which has been applied for decades without excessive concern), the evidence of prompt recovery indicates that coppice management remains a viable strategy even—or maybe even more—under the new conditions offered by the rapid modernization of the forest product sector and markets.

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