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# Soil and forest regeneration after different extraction methods in coppice forests

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ABSTRACT

Coppice is considered the oldest form of sustainable forest management in the Mediterranean area. Generally, it produces rapidly woody biomass and environmental benefits. This research was implemented through an experimental design based on two steps: analyzing the impact of silvicultural treatment (coppice with standards) and logging on forest soil and tree regeneration. It included the soil and regeneration recovery capacity of forests managed as coppice related to different logging systems and treatments applied over a six-year period. The findings demonstrated that tree species regeneration composition was not affected by silvicultural treatment and only slightly by harvesting system. Instead, the physical, chemical and biological soil features were only marginally affected by the silvicultural treatment applied, but strongly impacted by harvesting operations, with clear differences between the systems. The least damaging harvesting system was TLS (Tree Length System) followed by FTS (Full Tree System) and SWS (Short Wood System) that showed a more intense impact. This trend started only six months after harvesting and continued for more than 36 months post-harvesting in a lesser dynamic. The recovery of coppicing was almost complete 36 months after harvesting, without substantial differences between logging systems. Recovery from logging showed a clear positive trend, but 52 months after harvesting only the TLS area had completely recovered. For FTS and SWS, recovery occurred but was very weak.

## 1. Introduction

Coppicing is considered the oldest form of sustainable forest management and recent studies assessed that over 23 million hectares in the Mediterranean area are managed in this way (Unrau et al., 2018). Its past and current application is mainly due to its capacity to contribute to rural livelihoods, the bio-economy, environment and cultural heritage (Szabò, 2010; Unrau et al., 2018). With its unique characteristics, coppicing represents a flexible management system that requires low inputs, thus meeting the needs of rural societies and medium-small-scale businesses (Espelta et al., 1995; Franklin and Forman, 1987; Marchi et al., 2016; Venanzi et al., 2016; Unrau et al., 2018).

Coppice management went through a period of crisis starting at the beginning of the 20th century, when the concept of high forest management became prevalent. This option was generated fundamentally by economic and ecological or "ecologistic" aspects (Bičík et al., 2001; Lo Monaco et al., 2014; Lo Monaco et al., 2011; Notarangelo et al., 2018).

Despite the reduction of coppice forest area, new interests have re-activated this management system related to landscape, environmental, social and economic aspects (Venanzi et al., 2016). Forest coppice characterizes landscapes, especially in mountainous areas of central, eastern and southern Europe (Marchi et al., 2016). Some recent findings in ecological and forestry research have underlined that coppice forests protect and stabilize critical slopes and positively contribute to biodiversity conservation (Matula et al., 2019; Müllerová et al., 2015; Vild et al., 2013). Moreover, these forest systems, with their inherent environmental and ecological characteristics, show enviable qualities of resilience, with significant adaptability to climate change (Imamura et al., 2017; Unrau et al., 2018).

Oak species coppices were formerly important sources of structural timber (railway sleepers), firewood and charcoal (Picchio et al., 2011b), as well as litter collection and pasture (Gimmi et al., 2008). This management system, in the Mediterranean area, generally produces woody biomass rapidly (on average one cutting cycle every 12–18 years). In Italy, the main management system for this species is coppice with standards (about 70–120 standards/ha).

The recent market for Turkey oak (*Quercus cerris* L.) wood is for fuel wood, from both coppice and high forest management.

Turkey oak coppice forests grow mainly in the Mediterranean area (Bajraktari et al., 2018; Picchio et al., 2009). In Italy, they extend for over 1,000,000 ha, representing 11.5% of the national woodland, 9.7% of the forest area and 3.4% of the land surface (IFNC, 2007).

Recent studies (Marchi et al., 2016; Venanzi et al., 2016) on coppicing in the Mediterranean area highlighted that within a

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short time after harvesting, soil and regeneration characteristics undergo alterations. Marchi et al. (2016) assessed the impact of silvicultural treatment and harvesting operations on tree regeneration composition and soil characteristics in a period of 0–3 years after harvesting. Their findings demonstrated that tree species regeneration composition was not significantly affected by silvicultural treatment or harvesting operations. However, physical, chemical and biological soil features were only marginally affected by the silvicultural treatment applied but strongly impacted by harvesting operations.

Venanzi et al. (2016) assessed the impact on soil generated by the final harvesting of chestnut coppice with standards management system, in a period of 0–2 years after harvesting. Their findings demonstrated that physical, chemical and biological soil features were only in part affected by silvicultural treatment applied, but strongly impacted by harvesting operations.

Soil and regeneration characteristics could be influenced by coppicing (silvicultural treatment) due to the modified input of light, heat and water, as found for different treatments and management systems in other studies (Olajuyigbe et al., 2012; Picchio et al., 2018a). One of the strongest soils and regeneration degradation sources connected with coppicing is machinery traffic, which may cause compaction, soil horizon mixing and topsoil removal (Korb et al., 2007; Klvac et al., 2010; Williamson and Neilsen, 2000; Grigal, 2000).

Machinery traffic, or rather logging operations and systems, can differ depending on site characteristics, silvicultural management, technological level and timber assortments (Vusić et al., 2013; Picchio et al., 2018b). There have recently been significant technological innovations in forest logging and mechanization (Spinelli et al., 2019; Tolosana et al., 2018). However, traditional mechanization and logging systems are still widespread (Picchio et al., 2011a; Laschi et al., 2016).

In the last five years, studies were implemented focusing on the effects of silvicultural treatments and logging operations on forest soil and regeneration. However, it is rare that companies are required to take into account the impact of their operations on the land and on forest sustainability, or rather, to consider the real application of sustainable forest management as suggested by Forest Europe (Bertolotto et al., 2016; Picchio et al., 2016). Minimizing ground and regeneration damage caused by silvicultural treatments and forest operations remains an important topic. Some studies suggested to minimize the area of soil disturbance and compaction by appropriate operation planning (Mederski, 2006; Picchio et al., 2018b, 2019a), careful execution (Cambi et al., 2015, 2016) and suitable mechanization (Marchi et al., 2014; Picchio et al., 2012, 2018a; Proto and Zimbalatti, 2016; Proto et al., 2018). All this is in consideration of the fact that adequately managed forest ecosystems are claimed to be highly resilient in the long-term (Sánchez-Moreno et al., 2006).

In coppice systems the impacts due to silvicultural treatment (mainly canopy removal), separate forest operations and their interactions are very often a heated subject of discussion, but detailed scientific results are needed to seriously tackle the problem and provide suggestions and best practices. In particular, in order to improve silvicultural management and logging methods, better knowledge is needed on the recovery time of managed forest ecosystems. This is an important issue both for high forests and coppices (Unrau et al., 2018) and is one of the main goals of sustainable and optimal forest management (Sist and Nguyen-Thé, 2002; Sist et al., 2003).

Other important issues related to coppice management are represented by the dynamics of recruiting new individuals into existing populations and biodiversity conservation. Even if the present conditions of genetic density and management could tend to prevent population renewal, some authors (Espelta et al., 1995; Retana et al., 1992; Marchi et al., 2016) found that the seedling bank dynamics reinforce the role of gap formation through small- or large-scale perturbations in population turnover.

Coppicing maintains a cyclical pattern of extreme changes in ground-level light penetration (Buckley, 1992; Joys et al., 2004; Unrau et al., 2018), producing heterogeneous mosaics of forest in various stages of succession that harbor a rich variety of animals and vascular plants (Hédl et al., 2010; Benes et al., 2006; Bugalho et al., 2011; Spitzer et al., 2008; Vodka and Cizek, 2013).

Starting from this knowledge and in order to develop new studies on coppicing effects, the experimental design was implemented in two steps:

- analyzing the impact of silvicultural treatment and logging on forest soil and tree regeneration;
- and particularly, a new approach for assessing soil and tree regeneration, the recovery capacity of forests managed as coppice.

With the aim of acquiring a better comprehension of some ecological and productive aspects of forest coppice management, the impacts due to silvicultural treatment and forest operations were investigated. Soil and tree regeneration conditions in a Turkey oak coppice located in central Italy were monitored for a period of between one and six years. This study was an implementation and extension of a previous research (Marchi et al., 2016) with the following objectives: i) to investigate the impact of silvicultural treatment on tree regeneration and soil condition; ii) to find out how both silvicultural treatment and forest operations influence tree regeneration and soil characteristics; iii) to assess the impact of different types of mechanization and logging systems on tree regeneration and soil condition; iv) to assess the recovery capacity of tree regeneration and soil after harvesting.

New investigations were conducted on the same stands in order to assess the recovery dynamics in relation to injury and mechanization levels and treatment applied in a particularly long period of six years. This continuing research aimed at assessing the effect of coppicing on some soil characteristics and tree regeneration; understanding a possible treatment return time; and evaluating the existence of "mechanization-best practices". Knowing these aspects completely or partially is a key factor in the sustainable management of coppice forests in the Mediterranean area and is important for supporting forest managers in selecting forest operations.

## 2. Material and methods

### 2.1. Study sites

The studied Turkey oak coppice with standards was located in Central Italy, Umbria Region, Castel Giorgio municipality (42°68′36.16″N, 11°97′40.55″E). The forest stand harvested was about 95 ha, with homogeneous elevation, slope gradient and roughness: 600 m a.s.l., 25% and with ca 7% of the surface presenting obstacles to machinery traffic, respectively. The accessibility of the forest is fairly good, even if the road network in the area did not include permanent skid trails.

The soil is volcanic, with considerable depth (ranging from 0.7 to 1.1 m), and belongs to the "Typical Haplustepts fine, mixed, mesic" type (USDA classification). It is a non-hydromorph brown soil, with an acidic sub-acidic reaction. The soil has a high content of silt, 52.4%. There is 41.6% of sand while the clay content is low at 6.0%, therefore the soil can be ascribed to the Silty-Loam (SL) class. Along with the granulometric values and through the Soil Water method (Saxton et al., 1986), the soil field capacity was calculated (CC) at 26%.

### 2.2. Treatment and logging methods

The coppice was clear-cut at an average growth age of 19 years, releasing 95 standards per hectare. The harvesting operation was completed within approximately 200 days.

Three logging systems (Corona et al., 2015) were included in the investigation:

1) Area TLS (about 20 ha), where the logging system was Tree Length System;
2) Area FTS (about 20 ha), where the logging system was Full Tree System;
3) Area SWS (about 20 ha), where the logging system was Short Wood System.

Three control plots were selected:

1) Area C1 (about 10 ha) - unharvested and not impacted for more than 16 years, near the TLS area;
2) Area C2 (about 10 ha) - unharvested and not impacted for more than 16 years, near the FTS area;
3) Area C3 (about 10 ha) - unharvested and not impacted for more than 16 years, near the SWS area.

For all the areas studied, felling was motor-manual performed by three teams of two operators equipped with Stihl MS 362 chainsaws.

For the TLS area, bunching and extraction was done by winching uphill using a farm tractor equipped with a forest winch with a pulling force of 60 kN and 100 m of 12 mm diameter cable. The four-wheeled tractor was a SAME 85 kW, weighing 4800 kg. The tires, front 380/60 R30 and rear 420/70 R30, had a medium amount of wear. The tractor moved in some cases on the forest floor and a winching operation was conducted from the forest road. The delimbed trees were winched directly from the felling site and the average single load size per extracting cycle was 0.960 t.

For the FTS area, bunching and extraction was done by winching uphill using the same type of machinery as the TLS area. This tractor moved in some cases on the forest floor and a winching operation was conducted from the forest road. The trees were winched directly from the felling site and the average single load size per extracting cycle was 1.090 t.

For the SWS area, bunching and extraction was done uphill using a farm tractor (the same as in the previous areas) equipped with a forest grapple. The short logs (2.2 m in length) were picked up directly from the felling and processing site and the average single load size per extracting cycle was 0.401 t.

For all three systems, the tractors also moved on the forest floor due to the absence of tracks, but the frequency for the first two systems (TLS and FTS) was considerably less than SWS. In this last system the tractor needed to reach all the felling sites directly (in some cases several times) in order to pick up the logs.

Pre-harvest dendrometric characteristics (Table 1) were obtained using standard forest measurement techniques on thirty randomly selected circular plots with a 20 m radius, each therefore covering an area of 1256 $m^2$.

For all harvested areas the released scattered standards were 95 trees $ha^{-1}$. These standards were of three age classes: about 19-years-old (60%), about 38-years-old (30%), and about 57-years-old or more (10%). In addition, as prescribed by the Regional Forestry Regulation, about one tree per hectare was left for indefinite aging. The dendrometric data collected before harvesting showed average values with similar growth trends (Table 1).

The post harvesting measurements of regeneration and soil characteristics were taken approximately 6, 16, 36 and 52 months after coppicing.

### 2.3. Analytical methods

The impact on soil due to silvicultural treatment and forest operations was assessed on six randomly selected sample plots (SP) for each area (TLS, FTS, SWS, C1, C2, and C3). Each SP consisted of a circular area of 113 $m^2$. For the SPs of the three harvested areas (TLS, FTS and SWS), two different points (PO) were selected based on a visual assessment (e.g. the presence or absence of bent understory, crushed litter, ruts or soil mixing) to represent disturbed and undisturbed soil conditions, respectively. In order to determine soil physical-chemical characteristics Soil Texture, Bulk Density (BD), Penetration Resistance (PR), Shear Resistance (or strength) (SR), Organic Matter (OM) and pH were evaluated in each PO.

For the particle size distribution three soil samples in each area were taken randomly from the top 30 cm of soil (Marchi et al., 2016). Rock fragments (particles with > 2 mm diameter) were removed from the air-dried samples by sieving. Silt, clay and sand were determined using the Andreasen pipette method (Picchio et al., 2012). These fractions were used to find the soil classes using a textural USDA triangle (Gee and Bauder, 1986).

BD, PR and SR were determined through the methods proposed in Marchi et al. (2016) and expressed in Mg $m^{-3}$, MPa and t $m^{-2}$, respectively.

The pH value was measured using potentiometric analysis, in soil/saline solution suspensions (soil-KCl 1 mol) in a 1:2.5 proportion.

**Table 1**
Pre-harvest (TLS, FTS, SWS) and control (C1, C2, C3) plots dendrometric characteristics.

| Area | Shoots | Standards | Shoots | Standards | Shoots | Standards | Density* [trees/ha] | Basal area [$m^2$/ha] | Above-ground biomass stock | Above-ground biomass harvested |
|---|---|---|---|---|---|---|---|---|---|---|
| | Age [years] | | DBH* [cm] | | Height* [m] | | | | | |
| | | | | | | | [$m^3$/ha] | [$m^3$/ha] | | |
| TLS | 18 | 45 | 16.2 ± 3.2 | 28.4 ± 5.2 | 14.8 ± 1.1 | 18.2 ± 1.5 | 1520 ± 57 | 30.5 | 239.8 | 201.2 |
| FTS | 20 | 50 | 16.3 ± 2.1 | 34.2 ± 6.5 | 16.5 ± 1.8 | 17.4 ± 1.9 | 1184 ± 95 | 25.0 | 220.5 | 180.4 |
| SWS | 18 | 46 | 12.4 ± 2.0 | 29.5 ± 9.4 | 16.4 ± 2.1 | 18.1 ± 1.1 | 1873 ± 35 | 22.4 | 210.4 | 170.7 |
| C1 | 16 | 39 | 14.1 ± 8.4 | 26.3 ± 7.2 | 12.5 ± 1.8 | 18.1 ± 1.9 | 1695 ± 34 | 26.1 | 212.1 | – |
| C2 | 21 | 52 | 19.5 ± 6.2 | 32.1 ± 1.0 | 16.9 ± 2.1 | 19.7 ± 2.5 | 1123 ± 79 | 31.8 | 274.1 | – |
| C3 | 19 | 46 | 14.3 ± 9.1 | 30.0 ± 8.2 | 16.7 ± 1.6 | 19.1 ± 1.8 | 1794 ± 53 | 27.6 | 235.2 | – |

* (average ± SD).

OM measurement was performed by incineration in a mitten at 400 °C for 4 h following the thorough elimination of water and pre-treatment at 160 °C for 6 h.

To assess the soil area impacted by the dragged logs and moving machinery, soil surfaces were differentiated as those disturbed and undisturbed by visual assessment (e.g. presence or absence of bent understory, crushed litter, ruts or soil mixing). These post-operation analyses were conducted using research methods based on internationally shared protocols, elaborated and adapted to this study context as proposed in Picchio et al. (2011a, 2012). Linear transects were tracked to assess the impacted area (TLS, FTS and SWS) and the tree community composition (in all areas: TLS, FTS, SWS, C1, C2, and C3). As described in Marchi et al. (2016); a systematic sampling method was applied in each area. Each transect was rectangular in shape (1 m × 50 m) and established using a compass and tape measure.

Biological analyses were also conducted to better understand the soil impact level. The QBS-ar index was used for this as it is very useful, being extremely sensitive to 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. (2016) and Marchi et al. (2016).

To assess the effect of coppicing on some soil characteristics, tree regeneration was also studied. The tree composition of natural regeneration was analyzed through the Species Importance Value (SIV) index, calculated for each species as reported in the literature (Marchi et al., 2016; Picchio et al., 2018a).

The regeneration species diversity index was computed using the Shannon-Wiener information function (Ozçelik et al., 2008) as:

$$H' = -\Sigma\,(ni/n)\,\mathrm{Ln}\,(ni/n)$$

where:

ni is the SIV of a species and n is the sum of the total SIV of all species.

The tree composition of natural regeneration was assessed using species richness.

Species richness was defined as the total number of species sampled. The Shannon index (Pielou, 1966; Begehold et al., 2016) is based on information theory and the degree of difficulty in accurately predicting the next species sampled. This diversity index is sensitive to changes in rare species, has good discriminant ability, and is well represented in the literature (Burton et al., 1992). Biodiversity indices were compared by year and by type of logging system. The structural evenness index was calculated as reported in Begehold et al. (2016):

$$J = H'/\mathrm{Hmax}$$

where H′ is the number derived from the Shannon diversity index and Hmax is the maximum value of H'.

This index varies between 0 and 1, where a value of 1 denotes an exact uniform distribution. The Shannon index is a model measuring species diversity and the degree of homogeneity in species abundance. One of its applications is to correctly estimate the anthropogenic impact on ecological systems.

### 2.4. Statistics

Statistica 7.1 (2007) software was used to implement statistical analyses. Data distribution was plotted and checked for normality and homogeneity of variance via Lilliefors and Levene tests. To check differences between treatments the *t*-test, ANOVA or MANOVA, were applied. The data, which were not normally distributed and with insufficient homogeneity of variance, were statistically processed using the nonparametric ANOVA Kruskal-Wallis test.

In order to determine the correlation between the QBS-ar, BD, PR and SR, a nonparametric correlation analysis (Spearman correlation matrix) was applied. The same test was applied to assess the possible existence of a recovery trend for the main soil characteristics. Principal Component Analysis (PCA) was applied to investigate any linear correlations between the treatments studied. To minimize the scaling effect due to the different measurement units, the data corresponding to each independent variable were standardized using box-cox transformation.

## 3. Results

### 3.1. Analysis of the impacted surface

The forest soil surface clearly impacted by forest operations (presence of bent understory, crushed litter, ruts or soil disturbance) differed among the three logging systems. The statistical analysis showed significant differences among the average values. The lowest value was for TLS area and the highest for SWS (Table 2).

### 3.2. Physical and chemical analyses of soil

The post harvesting analysis conducted approximately 6, 16, 36 and 52 months after coppicing, showed no statistically significant differences regarding soil moisture between the treatments during the same sampling period. However, statistically significant differences between sampling periods were found (average moisture: 36 ± 5%; 38 ± 7%; 28 ± 6%; 54 ± 10%) for 6, 16, 36 and 52 months after coppicing, respectively. In the control areas, soil moisture showed the same trend, but with slightly higher values (difference range of about +3% to +5%).

The soil BD data showed statistically significant differences among the three treatments, soil types and four periods (Table 3). In particular, it was clearly higher in the disturbed areas than undisturbed ones in the first three periods, with higher impact in the FTS than SWS and the better situation shown for the TLS. Analysis of the last period (52 months after logging) showed a recovery of soil BD for the TLS area, while for the other areas (FTS and SWS) there were again higher values in the disturbed areas. A clear BD recovery was shown for all three areas, starting 16 months after logging activities.

The BD was also clearly affected by the uncovering effect due to coppicing, in particular, it was higher in the harvested but undisturbed area than in the control ones for the first two periods. Analysis of the last two periods (36 and 52 months after logging) showed a recovery of soil BD for all three areas.

The soil penetration resistance (PR) data showed statistically significant differences among the three treatments, soil types and four periods (Table 4). In particular, it was clearly higher in the disturbed areas than undisturbed ones in the first three periods, with the highest impact in the TLS, followed by SWS and FTS. Analysis of the two last periods (36 and 52 months after logging) showed a recovery of PR for the three areas. It was not affected by the uncovering effect due to coppicing.

The soil Shear Resistance (SR) data showed statistically significant differences among the three treatments, soil types and four periods (Table 5). It was clearly higher in the disturbed areas than

**Table 2**
Soil area impacted by bunching and extraction activities (ANOVA results; average ± SD).

| Area | p-value | Disturbed soil | Undisturbed soil |
|---|---|---|---|
| TLS | <0.05 | 3.6 ± 1.1% a | 96.4% |
| FTS | | 31.4 ± 7.7% b | 68.6% |
| SWS | | 44.7 ± 9.8% c | 55.3% |

**Table 3**
Results of the ANOVA and Tukey test for BD (average ± SD), difference tested between disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | Bulk density [g/cm $^3$] | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 0.773 ± 0.098a | 0.903 ± 0.090b | 0.665 ± 0.116c | 0.669 ± 0.026c | < 0.05 |
| | Disturbed | 0.982 ± 0.080b | 1.157 ± 0.188d | 0.799 ± 0.139a | 0.755 ± 0.135a,c | |
| C1 | Control | 0.687 ± 0.101c | 0.687 ± 0.101c | 0.687 ± 0.101c | 0.687 ± 0.101c | |
| FTS | Undisturbed | 0.752 ± 0.184a | 0.854 ± 0.104c | 0.760 ± 0.108a | 0.759 ± 0.098a | < 0.05 |
| | Disturbed | 1.123 ± 0.217b | 1.248 ± 0.174d | 0.969 ± 0.081e | 0.875 ± 0.124c | |
| C2 | Control | 0.758 ± 0.205a | 0.758 ± 0.205a | 0.758 ± 0.205a | 0.758 ± 0.205a | |
| SWS | Undisturbed | 0.690 ± 0.094a | 0.808 ± 0.109c | 0.739 ± 0.177a | 0.720 ± 0.089a | < 0.05 |
| | Disturbed | 0.911 ± 0.101b | 1.048 ± 0.181d | 0.906 ± 0.164b | 0.816 ± 0.122c | |
| C3 | Control | 0.719 ± 0.128a | 0.719 ± 0.128a | 0.719 ± 0.128a | 0.719 ± 0.128a | |

**Table 4**
Results of the ANOVA (average ± SD) and Tukey test for penetrometer resistance data, difference tested between disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | Penetration resistance [MPa] | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 0.13 ± 0.01a | 0.10 ± 0.01a | 0.15 ± 0.02c | 0.11 ± 0.02a | < 0.05 |
| | Disturbed | 0.29 ± 0.01b | 0.27 ± 0.02b | 0.24 ± 0.01d | 0.13 ± 0.01a | |
| C1 | Control | 0.11 ± 0.02a | 0.11 ± 0.02a | 0.11 ± 0.02a | 0.11 ± 0.02a | |
| FTS | Undisturbed | 0.09 ± 0.02a | 0.10 ± 0.01a,c | 0.13 ± 0.01c | 0.13 ± 0.02c | < 0.05 |
| | Disturbed | 0.23 ± 0.02b | 0.23 ± 0.01b | 0.21 ± 0.01d | 0.16 ± 0.02e,c | |
| C2 | Control | 0.13 ± 0.02c | 0.13 ± 0.02c | 0.13 ± 0.02c | 0.13 ± 0.02c | |
| SWS | Undisturbed | 0.09 ± 0.01a | 0.09 ± 0.01a | 0.10 ± 0.01a | 0.11 ± 0.02a | < 0.05 |
| | Disturbed | 0.22 ± 0.03b | 0.22 ± 0.02b | 0.19 ± 0.01c | 0.14 ± 0.01d | |
| C3 | Control | 0.11 ± 0.01a | 0.11 ± 0.01a | 0.11 ± 0.01a | 0.11 ± 0.01a | |

**Table 5**
Results of the ANOVA (average ± SD) and Tukey test for shear resistance data, difference tested between disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | Shear resistance [t/m $^2$] | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 3.62 ± 0.88a | 2.47 ± 0.91c | 2.59 ± 0.87c | 2.61 ± 0.72c | < 0.05 |
| | Disturbed | 8.77 ± 2.48b | 5.46 ± 1.26d | 4.99 ± 1.05d | 2.73 ± 0.90c | |
| C1 | Control | 2.69 ± 1.01c | 2.69 ± 1.01c | 2.69 ± 1.01c | 2.69 ± 1.01c | |
| FTS | Undisturbed | 2.38 ± 1.20a | 2.79 ± 1.15a | 2.51 ± 0.87a | 2.89 ± 1.05a | < 0.05 |
| | Disturbed | 6.33 ± 2.11b | 6.19 ± 0.98b | 5.21 ± 1.01c | 3.22 ± 0.75a,d | |
| C2 | Control | 2.78 ± 0.93a | 2.78 ± 0.93a | 2.78 ± 0.93a | 2.78 ± 0.93a | |
| SWS | Undisturbed | 1.69 ± 0.61a | 2.25 ± 0.87c | 2.57 ± 0.61c | 2.89 ± 0.94c | < 0.05 |
| | Disturbed | 5.47 ± 1.16b | 5.17 ± 0.82b | 4.96 ± 1.24b | 3.46 ± 1.07d | |
| C3 | Control | 2.87 ± 1.02c | 2.87 ± 1.02c | 2.87 ± 1.02c | 2.87 ± 1.02c | |

undisturbed ones in the first three periods, with highest impact in the TLS and FTS areas and a better situation shown for the SWS. Analysis of the last period (52 months after logging) showed a recovery of soil SR for the TLS and FTS areas, while for the other area (SWS) there were again higher values in the disturbed area. A clear recovery was shown for all three areas, starting 16 months after logging activities. The SR was not clearly affected by the uncovering effect due to coppicing.

The silvicultural activities performed significantly affected the soil OM content, but the data showed statistically significant differences between the three treatments, soil types and four periods (Table 6). It was clearly lower in the disturbed areas than undisturbed ones in the first two periods for TLS and FTS and in the first three periods for SWS. The highest impact was in the SWS area and the better situation was shown for the TLS and FTS. Analysis of the last period (52 months after logging) showed a recovery for the three areas. The OM was not negatively affected by the uncovering effect due to coppicing.

The soil Inorganic Carbon (IC) content was not affected by coppicing, while it was slightly affected by the different logging systems applied (Table 7). In particular, it was slightly lower in the disturbed areas than undisturbed ones. The highest difference between disturbed and undisturbed soil was in the SWS area.

The pH is an important soil characteristic, due to the fact that its variations influence various pedological parameters and processes (Astolfi et al., 2011). However, in this study (Table 8), this parameter did not seem to have been clearly influenced by silvicultural treatment or logging operations.

**Table 6**
Results of the ANOVA and Tukey test for organic matter content (average ± SD), difference tested among disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | Organic matter [%] | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 12.0 ± 0.9a | 13.5 ± 0.8e | 19.6 ± 0.9c | 21.3 ± 0.9c | < 0.05 |
| | Disturbed | 10.5 ± 1.8b | 11.1 ± 1.1b | 21.5 ± 1.2c | 22.4 ± 1.0c | |
| C1 | Control | 19.0 ± 1.2c | 19.0 ± 1.2c | 19.0 ± 1.2c | 19.0 ± 1.2c | |
| FTS | Undisturbed | 12.5 ± 1.1a | 14.7 ± 1.1e | 14.8 ± 0.8e | 14.7 ± 1.1e | < 0.05 |
| | Disturbed | 8.2 ± 1.11d | 13.3 ± 1.2a | 14.0 ± 1.2e | 14.8 ± 0.9e | |
| C2 | Control | 12.4 ± 0.9a | 12.4 ± 0.9a | 12.4 ± 0.9a | 12.4 ± 0.9a | |
| SWS | Undisturbed | 21.1 ± 1.6c | 21.0 ± 0.9c | 21.1 ± 0.9c | 21.1 ± 1.1c | < 0.05 |
| | Disturbed | 14.9 ± 1.2e | 14.0 ± 0.9e | 15.8 ± 1.14e | 18.6 ± 1.1c | |
| C3 | Control | 9.9 ± 1.2d | 9.9 ± 1.2d | 9.9 ± 1.2d | 9.9 ± 1.2d | |

**Table 7**
Results of the ANOVA and Tukey test for inorganic carbon content (average ± SD), difference tested among disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | Inorganic Carbon [%] | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 6.1 ± 0.8a | 6.9 ± 0.9c | 5.9 ± 1.0a | 5.9 ± 0.9a | < 0.05 |
| | Disturbed | 5.0 ± 1.1b | 5.1 ± 1.0b | 5.2 ± 0.9b | 5.0 ± 0.7b | |
| C1 | Control | 6.6 ± 0.8c | 6.6 ± 0.8c | 6.6 ± 0.8c | 6.6 ± 0.8c | |
| FTS | Undisturbed | 5.1 ± 1.1b | 5.0 ± 1.1b | 5.2 ± 0.9b | 5.2 ± 0.8b | > 0.05 |
| | Disturbed | 4.9 ± 1.0b | 5.1 ± 1.0b | 5.1 ± 1.1b | 5.1 ± 0.9b | |
| C2 | Control | 5.0 ± 0.8b | 5.0 ± 0.8b | 5.0 ± 0.8b | 5.0 ± 0.8b | |
| SWS | Undisturbed | 6.5 ± 1.2c | 6.4 ± 0.9a,c | 6.3 ± 0.8a,c | 6.4 ± 1.0a,c | > 0.05 |
| | Disturbed | 6.3 ± 1.0a,c | 6.3 ± 0.8a,c | 6.3 ± 1.1a,c | 6.4 ± 1.0a,c | |
| C3 | Control | 6.6 ± 1.0c | 6.6 ± 1.0c | 6.6 ± 1.0c | 6.6 ± 1.0c | |

**Table 8**
Results of the ANOVA and Tukey test for pH (average ± SD), difference tested among disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | pH | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 6.5 ± 0.7a | 6.4 ± 0.8a | 5.7 ± 0.9b | 5.5 ± 0.9b | < 0.05 |
| | Disturbed | 6.5 ± 1.0a | 6.6 ± 1.2a | 5.6 ± 1.1b | 5.5 ± 1.1b | |
| C1 | Control | 6.7 ± 0.9a | 6.7 ± 0.9a | 6.7 ± 0.9a | 6.7 ± 0.9a | |
| FTS | Undisturbed | 5.4 ± 1.2b | 5.3 ± 1.0b | 5.2 ± 0.9b | 5.2 ± 0.9b | < 0.05 |
| | Disturbed | 4.9 ± 1.1c | 4.6 ± 1.0c | 4.7 ± 1.0c | 4.7 ± 0.9c | |
| C2 | Control | 4.4 ± 0.9c | 4.4 ± 0.9c | 4.4 ± 0.9c | 4.4 ± 0.9c | |
| SWS | Undisturbed | 4.7 ± 1.1c | 4.7 ± 0.8c | 4.8 ± 0.9c | 4.7 ± 1.1c | > 0.05 |
| | Disturbed | 4.8 ± 1.2c | 4.7 ± 0.8c | 4.8 ± 1.1c | 4.7 ± 1.1c | |
| C3 | Control | 4.8 ± 1.0c | 4.8 ± 1.0c | 4.8 ± 1.0c | 4.8 ± 1.0c | |

### *3.3. Soil biodiversity analysis*

The QBS-ar index (Table 9) showed statistically significant differences among the three treatments, soil types and four periods. It was lower in the disturbed areas than undisturbed ones, but the recovery trend was clear 6 months after logging activities, with the highest impact in the SWS area and the better situation for the FTS, while 52 months after logging, the situation was similar for the three treatments. The QBS-ar was clearly affected by the uncovering effect due to coppicing only in the first period (6 months after logging), then recovery was completed.

As found in other studies (Venanzi et al., 2016; Marchi et al., 2016), microarthropod density was lower in all the areas involved in the impact caused by vehicles and logs, without any differences among the systems (data not shown). Moreover, immediately after the treatment, there was a statistically significant difference between the areas subject to silvicultural treatment (but not impacted by vehicles) compared to the control sites. In this case, however, it seems that the silvicultural treatment had a positive effect. For the impacted areas, the recovery trend was clear 6 months after logging and the situation was similar for the three treatments.

**Table 9**
Results of the Kruskall Wallis and Tukey test for QBS-ar index, difference tested among disturbed, undisturbed and control soil, for the three logging systems.

| Area | Soil type | QBS-ar | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 months | 16 months | 36 months | 52 months | |
| TLS | Undisturbed | 172a | 240c | 238c | 243c | < 0.05 |
| | Disturbed | 93b | 188a | 196a | 202d | |
| C1 | Control | 242c | 242c | 242c | 242c | |
| FTS | Undisturbed | 205d | 224f | 231c | 240c | < 0.05 |
| | Disturbed | 128e | 174a | 179a | 201d | |
| C2 | Control | 244c | 244c | 244c | 244c | |
| SWS | Undisturbed | 202d | 203d | 212d | 237c | < 0.05 |
| | Disturbed | 108b | 164a | 180a | 199d | |
| C3 | Control | 243c | 243c | 243c | 243c | |

### *3.4. Analysis of stand regeneration*

In the studied forest, for each of the ten tree species found (Fig. 1), there were statistically significant differences in distribution and presence, among the three treatments, and the four periods observed regarding a few species. Among the species, *Quercus cerris* showed the highest seedling and shoot (SS) density (ranging from 14,000 to 27,000 SS/ha). The TLS and FTS areas showed higher tree regeneration density than SWS area for all the periods observed. Between the four periods the tree regeneration density was similar 6 and 36 months after logging, while it was statistically different after 16 and 52 months. In particular, 16 months after logging, for the TLS and FTS areas there was an important tree regeneration increase, while 52 months after logging, for the TLS and FTS areas there was a decrease, but with values close to 25,000 SS/ha, always higher than those in the SWS area (22,000 SS/ha). As shown in Fig. 2, the decrease was more intense for seedlings (gamic renovation) than shoots (agamic renovation), with an average percentage composition analyzed at ca 10% shoots and 90% seedlings, 52 months after logging.

The Species Importance Value (SIV) analysis, showed that *Q. cerris* was the most important species in all treatments (Fig. 3), followed by *Fraxinus ornus*, *Castanea sativa* and *Prunus avium*, but with differences among treatments.

The tree species diversity, tested by the Shannon-Wiener and Evenness indices, showed different situations (Table 10); in the first step (after 6 months) coppicing slightly increased the diversity indices in comparison to the control areas. In particular, a better situation was shown for the FTS area and slightly lower for the TLS and SWS areas. The indices decreased 16 and 36 months after logging with respect

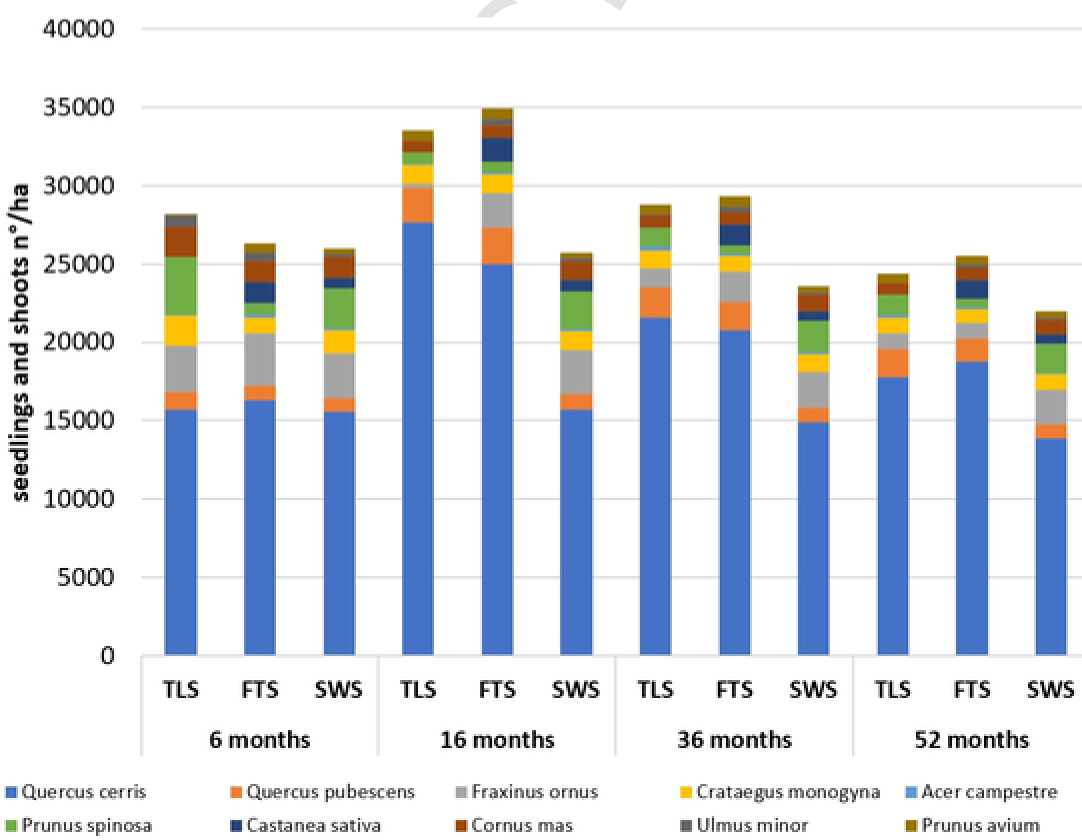


**Fig. 1.** Number of Seedlings and Shoots (SS) per species in the three treatments during the four periods studied (MANOVA test, $p < 0.05$; average).

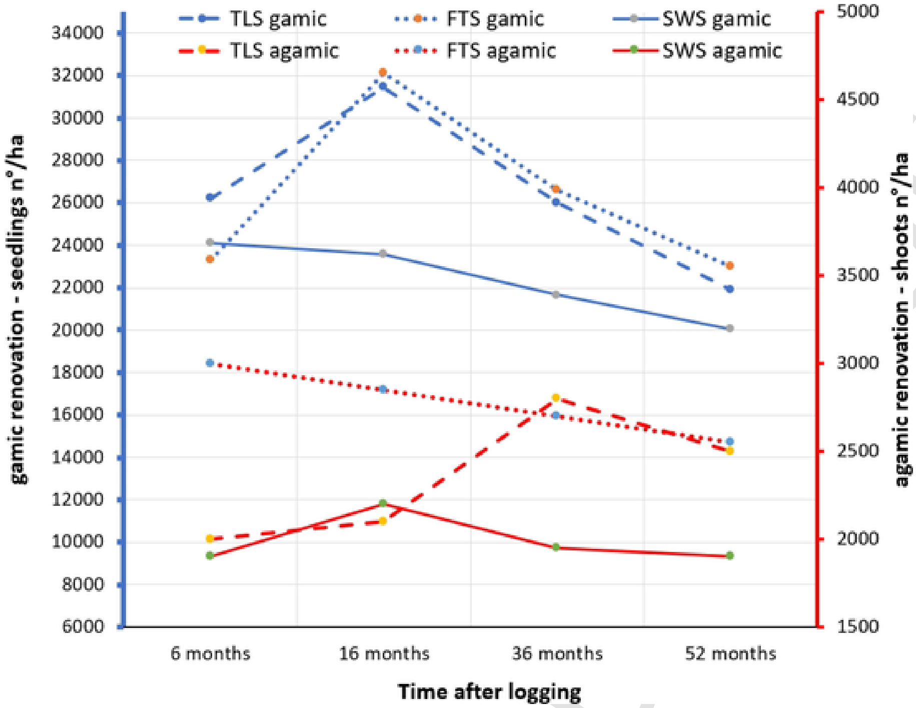


**Fig. 2.** Number of Seedlings and Shoots (SS) in the three treatments during the four periods studied (MANOVA test, $p < 0.05$; average).

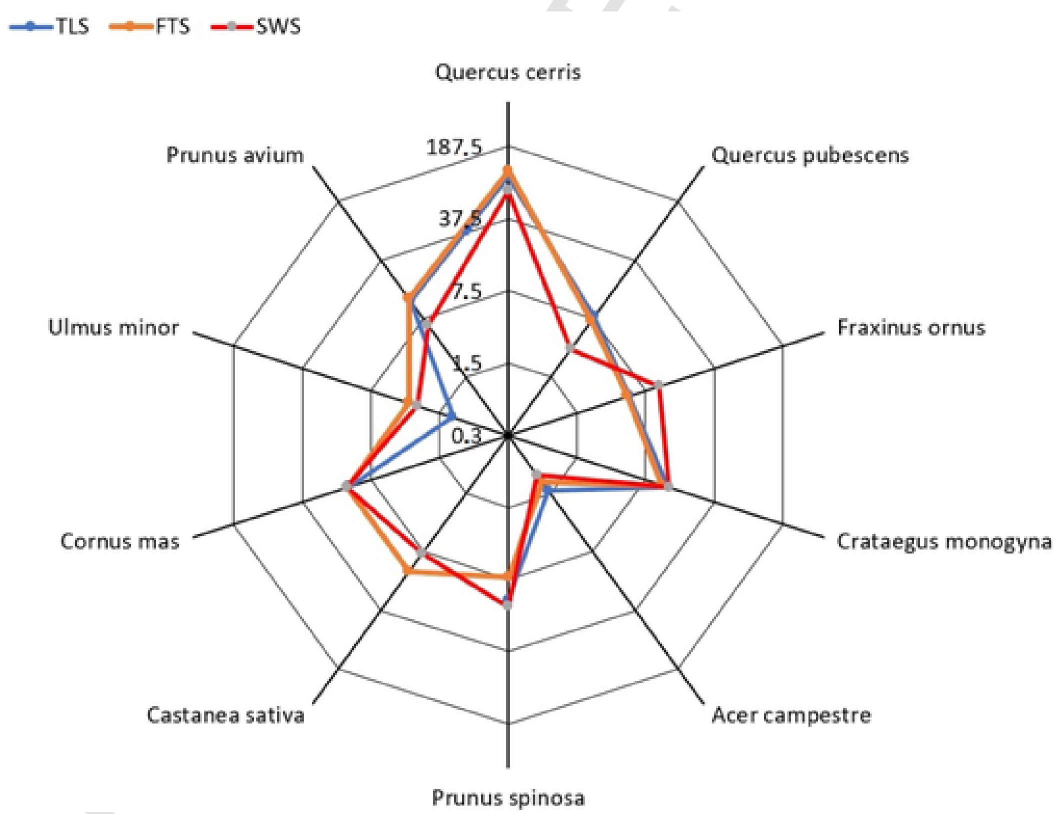


**Fig. 3.** SIV index for the three areas studied after 52 months.

to the control areas, but 52 months after logging a clear recovery was shown for the FTS and TLS areas, while for the SWS area the recovery trend was only starting.

## 4. Discussion

The logging system applied differently affected the extent of forest soil surface impacted by forest operations, as also shown in Picchio et al. (2019b) and Jourgholami et al. (2014). The more

**Table 10**
Tree species diversity indices for the three areas and four periods (Kruskall Wallis-test analysis, $p < 0.05$; average; from the Tukey test applied, different letters show groups with statistically significant differences).

| Area | Index | Periods (months) | | | | p-value |
|---|---|---|---|---|---|---|
| | | 6 | 16 | 36 | 52 | |
| TLS | Shannon's Index | 1.77a | 1.25b | 1.49c | 1.69a | < 0.05 |
| C1 | Shannon's Index | 1.73a | 1.72a | 1.72a | 1.74a | |
| FTS | Shannon's Index | 1.81a | 1.43c | 1.59c | 1.73a | |
| C2 | Shannon's Index | 1.74a | 1.74a | 1.72a | 1.72a | |
| SWS | Shannon's Index | 1.76a | 1.22b | 1.31b | 1.52c | |
| C3 | Shannon's Index | 1.72a | 1.74a | 1.74a | 1.73a | |
| TLS | Evenness Index | 0.77a | 0.64b | 0.65b | 0.73a | < 0.05 |
| C1 | Evenness Index | 0.89c | 0.89c | 0.89c | 0.89c | |
| FTS | Evenness Index | 0.79a | 0.70b | 0.73a | 0.76a | |
| C2 | Evenness Index | 0.90c | 0.89c | 0.91c | 0.88c | |
| SWS | Evenness Index | 0.75a | 0.64b | 0.63b | 0.66b | |
| C3 | Evenness Index | 0.87c | 0.88c | 0.88c | 0.88c | |

appropriate system for coppicing, in this situation of moderate slope (25%) and roughness seemed to be the TLS, followed by FTS and lastly SWS. In particular, the big difference between TLS and FTS was closely related to the considerable size of the tree canopies, which made winching over long distances complex. For this reason, the skidder needed to move more over the forest floor.

Soil BD, PR and SR were only marginally influenced by coppicing and full recovery was observed 16 months after logging. This was shown by the comparison of undisturbed soil surfaces in the coppiced areas with the control areas (without silvicultural treatment in the last decade). As found in similar studies (Venanzi et al., 2016, Marchi et al., 2016), these soil physical parameters could be affected by the weather, especially rain or snow, but due to the quick canopy regeneration in coppice management these impacts were limited to a period of few months after harvesting (< 16 months).

The effects of forest operations showed significant differences between disturbed and undisturbed soil samples for the three logging systems applied, with the highest impact being for FTS and SWS areas in the first periods analyzed. These impact levels have been observed in other studies where logs were skidded, and machinery also moved across the forest floor (Picchio et al., 2012; Cambi et al., 2015, 2016, 2017; Venanzi et al., 2016; Marchi et al., 2016; Tavankar et al., 2017). In the last period analyzed, 52 months after logging, BD, PR and SR showed an important, but not complete recovery with percentages of impact varying between 5% and 27%, higher for SWS and FTS than TLS area. These findings provided further evidence that there is a need to limit the forest soil surface directly affected by the moving of machinery and logs, even if recovery could be considered relatively fast. The better result shown by TLS was related to the limited movement of the tractor directly on the forest floor, in this case winching extraction was more used than skidding.

Soil organic matter content was influenced by coppicing and recovery was only clear 36 months after logging. As for the physical parameters, the impacts caused on the OM content were similar to those found in other studies (Venanzi et al., 2016; Marchi et al., 2016) and were limited to a few months after harvesting (< 36 months).

Differently from what was found by Venanzi et al. (2016) and Marchi et al. (2016), also logging activities showed significant modification of OM content but only for FTS and SWS areas. The recovery started 16 months after logging and was complete after 36 months. The decrease in OM content in the treated areas may be linked to canopy removal, which means a lack of leaves contributing to litter formation and an increase in the respiratory activity of soil microorganisms, the recovery shown was linked to the fast canopy regeneration.

As found in other studies (Venanzi et al., 2016; Marchi et al., 2016; Cambi et al., 2017; Picchio et al., 2018a,b), the pH did not show any clear statistical relation to treatments and periods. Instead the IC content seemed to be affected mainly by the logging operations (Picchio et al., 2018a,b). The biggest difference between disturbed and undisturbed soil was in the SWS area.

QBS-ar index was negatively influenced by coppicing, but recovery was clear 6 months after logging. This was shown by a comparison of the undisturbed soil surfaces in the coppiced areas with the control areas. Instead, the microarthropod density was positively influenced by coppicing in the first 6 months after harvesting, but the values became similar to the control 16 months after harvesting. These findings were similar to those in other studies (Venanzi et al., 2016; Marchi et al., 2016) and consistent with physical and chemical soil features.

As found for the physical and chemical soil parameters, the effects of forest operations showed significant QBS-ar index differences between disturbed and undisturbed soil samples for the three logging systems applied. The highest impact was for SWS and TLS areas (46.5% and 45.9%, respectively) and the lowest for FTS (37.6%) in the first periods analyzed. The assessed values have been observed in other studies where logs were skidded, and vehicles also moved across the forest floor (Picchio et al., 2012; Cambi et al., 2015, 2016; Venanzi et al., 2016; Marchi et al., 2016). Even if a start of the recovery trend was visible 52 months after logging QBS-ar index showed an important, but not complete recovery, with a percentage of impact close to 16%, similar for all the systems.

The QBS-ar values showed a significant correlation with soil compaction (Venanzi et al., 2016; Marchi et al., 2016) and as also observed by Blasi et al. (2013), most of the variation in the sample was explained by the different level of soil compaction rather than by physical habitat heterogeneity. This biological index was also influenced by the time taken for bunching-extraction operations with the SWS, the more time-consuming logging system having the highest impact.

This study showed that the soil of coppice forest is fragile in physical as well as chemical and biological terms and its balances are highly complex, as found also for high forest soils (Bertolotto et al., 2016; Picchio et al., 2018a; Picchio et al., 2016). These findings underline its vulnerability to natural or human disturbance (Vossbrink and Horn, 2004). As a consequence, impact assessment and recovery time are two extremely important topics in terms of forest management, and therefore the design and application of low impact logging methods (Picchio et al., 2018b; Picchio et al., 2019a). In this context, precision forestry could be an interesting approach to reduce impacts, through planning and when possible during the logging operations. However, operator training remains one of the principal necessities of reduced impact logging rather than mechanization level.

Other consequences of soil compaction are a decrease in permeability, and in the nutrient supply and growth of the root systems (Alakukku, 2000; Heinonen et al., 2002; Jourgholami et al., 2017). Directly linked to soil compaction, the expected increase in water runoff could facilitate the expansion and transmission of pathogens in the form of spores and rhizoids (Vannini et al., 2009).

A similar taxonomic composition of the forest community was found in the studied areas. The observed species were initially the same, then felling produced an abundance of heliophile species due to the increase in light, but after 36 months due to strong competition from stump re-sprouting this abundance decreased (Fig. 1). The TLS and FTS areas showed higher tree regeneration density than SWS for all the periods observed. The regeneration decrease was more intense for seedlings than shoots (Marchi et al., 2016), although the average percentage composition analyzed was of ca 10% shoots and 90% seedlings 52 months after logging, showing a persistence of seedlings regeneration also in a coppice system.

As found by Marchi et al. (2016), the SIV analysis showed that *Q. cerris* was the most important species in all the treatments (Fig. 3), followed by *F. ornus*, *C. sativa* and *P. avium*, but with differences in different areas, in particular FTS and TLS showed a higher SIV than SWS. This is mainly due to the lowest soil compaction and longest time spent on bunching-extraction operations for SWS (about 30% more than TLS and FTS), which finished in the month of May, often with new greenery already growing.

Tree species diversity, tested by the Shannon-Wiener and Evenness indices, showed that 6 months after harvesting the coppicing slightly increased the diversity indices compared to the control areas. The best situation was shown for the FTS area and slightly lower for the TLS and SWS areas. The indices varied after harvesting, decreasing 16 and 36 months after logging compared to the control areas. Recovery was shown only 52 months after logging for the FTS and TLS areas, while for the SWS area the recovery trend was only starting, due to the reasons stated above. As also found by Marchi et al. (2016), the silvicultural treatment did not affect species diversity and these results are supported by the Evenness index, which showed a very similar value to those of more complex silvicultural treatments, such as high forest.

Two principal component analyses (PCAs) (Fig. 4) were conducted to investigate any linear correlations between soil conditions and tree regeneration situations in the nine areas studied. For soil conditions, the principal components PC1 and PC2, explained 47% and 25% of the total variance, respectively. The PC1 and PC2 scores for the three logging systems (impacted and non-impacted soil situations) and the control are shown in Fig. 4. In general, the harvested areas with undisturbed soil showed a clear positive trend closely comparable to that of the control and similar among the three systems. The harvested areas with disturbed soil showed clear differences among the three systems applied: the best situation was for TLS, followed by FTS and lastly SWS. In detail, the TLS area had the highest recovery of physical and chemical soil parameters and tree regeneration, which implies that these parameters were closely associated with their PC1 scores, according to Marchi et al. (2016). Similarly, the SWS and FTS areas had the lowest recovery of the biological soil parameters and tree regeneration index, closely associated with their PC2 scores.

## 5. Conclusions

This study contributes to analyzing the impact of the silvicultural treatment and logging on forest soil, tree regeneration, assessment for soil and tree regeneration and the recovery capacity of forests managed as coppice. It aimed for a better comprehension of some ecological and productive aspects of forest coppice management, especially related to the impacts due to silvicultural treatment and forest operations. New investigations were performed in the same forest as a previous study, in order to learn about the recovery dynamics in relation to injuries caused by different logging systems and treatment applied over a six-year period. This continuing research focused on assessing the effect of coppicing on some soil characteristics and tree regeneration; on understanding the optimal return time for a sustainable treatment; and evaluating the existence of "forest logging best practices". These new findings are a key factor in the sustainable management of coppice forests in the Mediterranean area and are important for supporting the decision making of forest managers.

The results demonstrated that regeneration tree species composition was not impacted by silvicultural treatment and slightly by harvesting system. Instead, physical, chemical and biological soil features were only marginally impacted by the silvicultural treatment applied, but strongly by harvesting operations, with clear differences among systems. In general, the impact caused by vehicle movement on forest soils (off-track) is evident from the data of the physical-mechanical soil components. Therefore, when future forest operations are planned, a careful design of skid trails that limit any negative impact on the soil is recommended. Although skid trails limit the affected area, the concentration of damage is usually more evident.

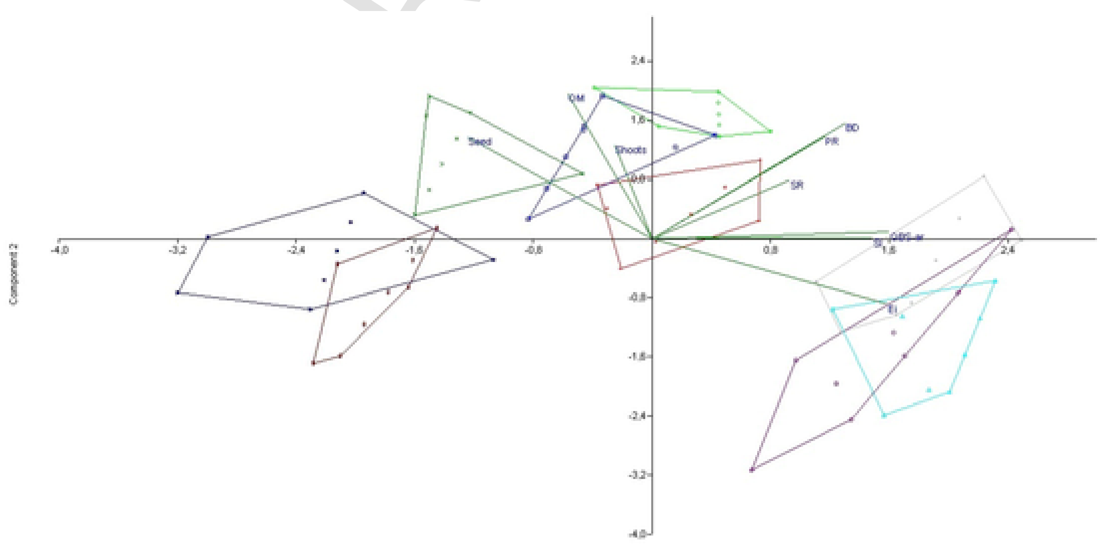


**Fig. 4.** Score plot of components PC1 and PC2 of the Principal Component Analysis referred to soil parameters and tree regeneration situations. The three control areas (light blue, violet and grey); TLS area with undisturbed soil (light green); FTS area with undisturbed soil (blue); SWS area with undisturbed soil (red); TLS area with disturbed soil (dark green); FTS area with undisturbed soil (dark blue); SWS area with undisturbed soil (dark red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The least damaging harvesting system was TLS, followed by FTS and SWS that showed a more intense impact. This was observed after just 6 months of harvesting and although it was weaker it remained for more than 36 months post-harvesting.

The recovery from coppicing impact was almost complete 36 months post-harvesting, without substantial differences among logging systems.

The recovery from logging impact showed a clear positive trend, but 52 months post-harvesting only for the TLS system was it possible to confirm, statistically, a complete recovery. For FTS and SWS systems the impact was still present even if much weaker.

From these findings it is possible to assert that for the logging systems FTS and SWS, recovery times of about 60–72 months are to be expected.

It would be interesting for future research to validate the effective recovery capacity from these types of stress on the soil and at the vegetation level.

Furthermore, it would be desirable to create designated skid trails that could be used to limit the impacted soil surface, hence preserving the rest of the area. The importance of studies such as these also lies in the possibility of deploying and updating the guidelines, criteria and indicators for sustainable forest management, as proposed by Forest Europe and as expected by a multitasking forest management system.

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