Proceeding Paper

Disturbances to the Ground and to the Stand in Beech Forests Due to Thinning Treatments Performed by Different Levels of Mechanization [†]

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Abstract: The aim of this work was to assess the possible impacts on the forest soil and stand due to silvicultural treatment and forest operations in a beech high forest. Even aged beech forests (*Fagus sylvatica* L.) in the Municipality of Cappadocia (L'Aquila) and in the Municipality of Vallepietra (Roma) were analyzed. The analysis of the soil and stand were performed in order to assess the effects attributable to applied silviculture and forest logging. Two different logging methodologies (in particular for the extraction) were applied: mules were used in the areas with greater slopes and with obstacles, while for the areas with better accessibility, mechanical means were used, in this case tractors. In detail, the main objective was to assess the disturbance on the ground and on the stand, generated by the two different levels of mechanization. In addition, it was also interesting to understand the possible effect on the soil and specifically on the partial uncovering where part of the tree canopy was removed. Only through an accurate cross-analysis of the studied parameters and indices could the anthropogenic impacts on the soil and stand due to forest operations be highlighted according to the different logging methodologies applied. The main results showed that the disturbances caused to the soil and stand were essentially caused in the bunching and extraction operations. The importance of avoiding or limiting the continuous passage of vehicles and animals on forest soil clearly emerges, especially in conditions of high soil moisture. It is also important to use correct technologies that are adequate for the specific environmental characteristics and the work plan. Finally, it can be said that there was no difference in the disturbance caused by the two logging methods when compared. Substantial differences in terms of improvement can be defined when comparing the findings of this study with other research studies. This can be done by applying a different type of mechanization with a different logging system.

Keywords: forest logging; soil; beech forest; impacts; sustainable forest management

1. Introduction

Silvicultural treatment methods such as thinning are one of the most important issues that governs the quality and quantity of forest stands at the final cutting, especially in young even aged stands. Removing the poor quality trees and establishing the appropriate growth conditions for desired individuals are the most important objectives of thinning operations [1]. Some of the research results have revealed that thinning has a significant positive effect on the growth of the remaining trees and forest yield [2]. Development of young forest stands for final harvest depends on the quality and intensity of thinning operations. Indeed, thinning involves cutting within an immature stand to: (a)

stimulate diameter growth of remaining trees, and (b) increase the total value of merchantable wood [3]. Further silvicultural objectives of thinning operations may include improving the stand health rate and providing stand conditions for the natural regeneration of trees. All ecological aspects could be affected by the application of silvicultural treatments [4–6]. Changes in the levels of input of light, water, and temperature for the forest ecosystem can be induced by forest harvesting. Moreover, it is important to highlight that logging activities, with machine and load traffic, may cause soil compaction, soil horizon mixing, and topsoil removal [6–9]. Thus, soil degradation could reduce tree growth [10], and carbon dioxide efflux from the soil may change significantly [11].

Biodiversity conservation has long been a goal of European conservation policies [12,13]. However, although more than 25% of the land within the European territory has been assigned some level of protection for conservation, biodiversity continues to decline [14]. One factor contributing to this decline may be unsuitable management practices [14,15]. In this case, biodiversity monitoring is essential to support management decisions in maintaining multiple forest ecosystem functions [12,16,17].

Dendrometrical parameters such as forest density, spatial pattern, classification of residual and harvested trees, qualification of soil disturbance, and damage to residual trees are the main issues for thinning operations [18] aimed at limiting any permanent disturbance [1,5]. Wounds on the bole of residual trees can cause negative effects on tree growth and wood quality [19].

One of the main sources of risk is logging systems linked to silvicultural management and the final products. Although in recent times there have been significant innovations in forest operations [5,20], forest logging in Italy is often carried out by using traditional methods [20–22]. Specific studies focused on the effects of silvicultural treatment and logging activities on soil and trees are rare, or are overly guided by extreme currents of thought. Details focused on their environmental effects and recovery times are lacking, and as a result it is not easy to follow the sustainability pillars. It is also quite common that for these same reasons, companies are seldom required to take into account the impact of their operations.

Taking into consideration all that has been said, it can be deduced that the risk for soil degradation connected with frequent machine traffic is a major concern [10,11,23]. At the same time, it must also be considered that not all logging techniques have the same ecological footprint and their level of disturbance depends on site characteristics, silvicultural management, technological level, and product strategy [12,14].

In addition, the growing importance of responsible and sustainable forest management (SFM) will require more and more assessments of ground and stand disturbance in order to minimize possible damage [24–26].

The aim of this study was to assess the possible impacts on the forest soil and stand due to silvicultural treatment and forest operations in even aged beech forests (*Fagus sylvatica* L.) in the Municipality of Cappadocia (L'Aquila) and in the Municipality of Vallepietra (Roma), Italy.

In particular, the main objectives were:

a. to investigate the impact of silvicultural treatment on soil conditions;
b. to find out how both silvicultural treatment and forest operations influence soil characteristics;
c. to investigate the impact on soil conditions and remaining stand due to different levels of mechanization.

2. Material and Method

2.1. Site Description

The study stand was even aged beech high forests (*Fagus sylvatica* L.) managed as a shelterwood system. The stand was located in Central Italy, between two Regions: the

Lazio Region and the Abruzzo Region. Both study sites are Natura 2000 network areas and protected areas: Cappadocia Municipality falls under the SIC/ZPS Simbruini Mountains IT7110207 area and Vallepietra Municipality fall under the ZPS Simbruini-Ernici IT6050008, ZSC Autore Mountain e Central Simbruni Mountains and Regional Park of Simbruini Mountains areas.

2.2. Treatment and Logging Methods

The silvicultural system applied was a thinning from below with removal of 20% in volume and the harvesting method was the "Short Wood System". The forest operations were carried out from June to October 2018 by the same forest logging company. The felling and processing operations were done by chainsaw. Two different extraction systems were used; the first system involved using several teams of mules in the areas with a steeper slope, while a wheeled tractor equipped with forwarding bins on the front and rear side were was in the areas with better accessibility (John Deere 6130M).

2.3. Analytical Methods

Post-operation analyses were made to assess 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 a 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.

Soil disturbance was assessed on two randomly selected sample plots for each harvested forest area and on two selected control areas. 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 both systems, the disturbed soil and the undisturbed soil were identified and selected based on a visual assessment. In particular, the disturbed soil is represented by the soil affected by the passage of loads and vehicles and the undisturbed soil is the soil affected by only the silvicultural activity and the canopy uncovering. In addition, a control site was selected, which had not been affected by logging and silvicultural activities for more than 30 years. Research was carried out according to a specific methodology. In particular, attention was focused on observing the impact on the soil's chemical, physical, and biological characteristics.

In order to determine the soil's physical and chemical characteristics, researchers determined the soil texture, bulk density (BD), penetration resistance (PR), shear resistance (SR), organic matter (OM), and pH for each plot and stratum. For BD, PR, and SR, measurements were conducted according to the methods described in Marchi et al. [27] and expressed in $Mg\ m^{-3}$, MPa, and $t\ m^{-2}$, respectively. The pH value was measured as described in Venanzi et al. [28] using potentiometric analysis, in soil/saline solution suspensions (soil-KCl 1 mol) in a 1:2.5 proportion. As proposed by Venanzi et al. [29], 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.

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 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. [30] and Marchi et al. [27].

Damage to residual trees after thinning operations was evaluated following international protocols. Sampling was carried out before and after thinning, using the

systematic sampling plots to evaluate the condition of remaining trees [1,31,32]. The distance between the centers of the plots was 100 m, the shape of subplots was square, and the area of plots was 400 m² (20 m × 20 m). The number of sample subplots depended on the compartment area, and ranged from 26 to 36 sample subplots. The damage location, intensity, size, and cause were recorded following proposals by various authors [20,33,34].

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. The 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 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 extraction method.

3. Results

The study areas were affected by a different type of mechanization for the bunching and extraction operations. For a better understanding of the results listed below, the texture of the two areas is shown for a more articulated view of the soil ecosystem. Although both soils can be ascribed to the sandy loam category, the two areas differ slightly from each other in terms of percentage distributions (Camporotondo: sand 52.6%, silt 43.7%, and clay 3.7%; Vallepietra: sand 54.0%, silt 43.8%, and clay 2.2%).

3.1. Impacted Surface

The forest soil surface clearly impacted by forest operations differed between the two different mechanization levels used only in the Vallepietra site (Table 1).

Table 1. Results expressed as a percentage of the area impacted on total area of the transepts carried out. Data showed as mean ± std. Different letters indicate significant differences determined by Tukey's test ($p < 0.05$).

Site	Extaction System	*p*-Value	Tukey's Test	Impacted Surface	Not Impacted Surface
Camporotondo	Tractor	>0.05	-	24.2 ± 4.5%	75.8%
Camporotondo	Mule		-	27.8 ± 8.3%	72.2%
Vallepietra	Mule	<0.05	a	11.1 ± 3.2%	88.9%
Vallepietra	Tractor		b	23.0 ± 2.8%	77.0%

3.2. Stand Damage

The reported data (Table 2) show how most of the damaged trees in the analyzed sites belong to the co-dominant plane, with the exception of the Vallepietra site (mule extraction), which has a higher percentage of trees belonging to the dominant plane.

The localization of the damage indicates that these are mainly concentrated at the level of the collar with wound extension ranging from <10 cm² to 10–50 cm², indicating an extension of the damage found on the trees, which are very similar to each other. The damage mainly affected the outermost tissues such as the bark.

From the above values emerge the first observations regarding the parameters that showed statistically significant differences between the respective silvicultural and logging systems adopted.

First, it is possible to compare the percentages of damaged trees:

- 39.6% of the site Camporotondo extraction involved using the tractor;
- 38.0% of the site Camporotondo extraction involved using mules;
- 45.6% of the site Vallepietra extraction involved using mules;

- 32.8% of the site Vallepietra extraction involved using the tractor.

Table 2. Main data of the field surveys relating to the stand damage. Different letters indicate significant differences obained by Tukey's test ($p < 0.05$).

Description	Unit of Measure	Camporotondo		Vallepietra		*p*-Value
		Tractor	Mule	Mule	Tractor	
Damaged trees	%	39.6 [a]	38.0 [a]	45.6 [b]	32.8 [c]	<0.05
Diameter	cm	38.8	42.9	39.2	40.8	>0.05
Hierarchical Position	Index	Co-dominant	Co-dominant	Dominant	Co-dominant	>0.05
Localization	Index	Tree collar	Tree collar	Tree collar	Tree collar	>0.05
Extension	Index	10–50 cm²	10–50 cm²	<10 cm²	10–50 cm²	>0.05
Affected Tissue	Index	Bark	Bark	Bark	Bark	>0.05
Severity of injury	Index	Moderate	Moderate	Non-invasive	Moderate	>0.05
Cause	Index	Extraction 57%	Extraction 58%	Extraction 54%	Extraction 52%	>0.05
Distance from forest tracks	Index	0–2 m	0–2 m	0–2 m	2–4 m	>0.05

The data shows how the difference in the results between the two logging systems adopted is minimal in the Camporotondo area and therefore the intensity, not intended as the extent of the damage but as a percentage of damaged trees, is comparable between the two systems applied, without any substantial difference.

The divergence of the data occurs for the Vallepietra parcel, in which there is a higher percentage of damaged trees in the area extracted by mules, as compared to the other site where vehicles were used for the bunching and extraction operations.

3.3. Soil Physical and Chemical Features

The post harvesting analysis showed no statistically significant differences regarding soil moisture between the treatments during the sampling period.

The soil BD data showed statistically significant differences only for the Vallepietra site, between the two different types of extraction (Figure 1). In particular, the differences were clearly higher in the area affected by extraction by tractor.

The BD seemed to also be affected by the uncovering effect due to the treatment applied, in particular, it was higher in the undisturbed area than in the control one.
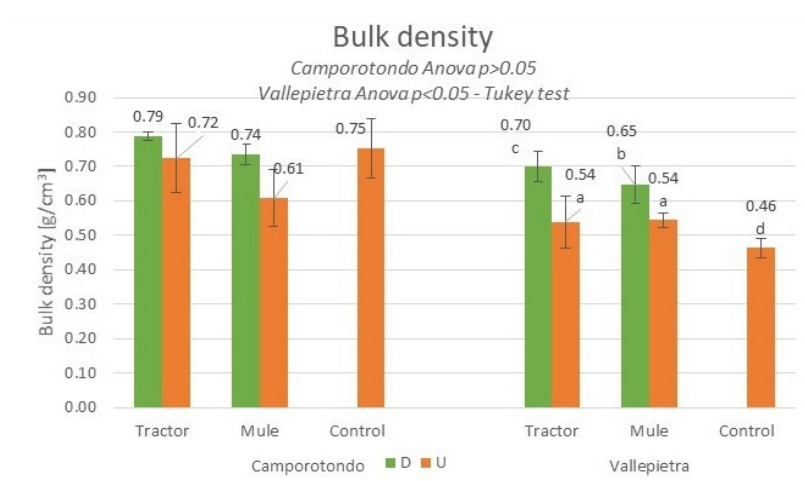

Figure 1. Results of the ANOVA and Tukey's test for bulk density, which was difference tested among disturbed (D), undisturbed (U), and control soil for the two mechanization levels. Different letters after means within each mechanization level indicate significant differences obtained by Tukey's test ($p < 0.05$).

The analysis of the two main mechanical characteristics of the soil, namely penetrometric and shear resistance, showed statistically significant differences between the treatments compared (Figure 2). Although these analyses concern the surface layer of forest soil, they are of considerable importance especially regarding gas exchanges, surface water permeability, and seed germination capacity.

The results obtained show how in the Camporotondo area in the disturbed soil (logging with tractor), penetrometric resistance values were found to be higher as compared to undisturbed soils. A similar situation occurred at sites extracted by mules. Statistical analysis shows significant differences between disturbed and undisturbed areas in both locations. The undisturbed soils of both sites show resistance to penetration values very similar to those obtained in the control area.

Analyzing the areas located in Vallepietra, a situation very similar to that of Camporotondo is observable, since in this case the highest penetrometric values were detected in the disturbed soils as well. The control area, on the other hand, presents intermediate penetrometric values as compared to those found in the disturbed and non-disturbed zones of both sites.
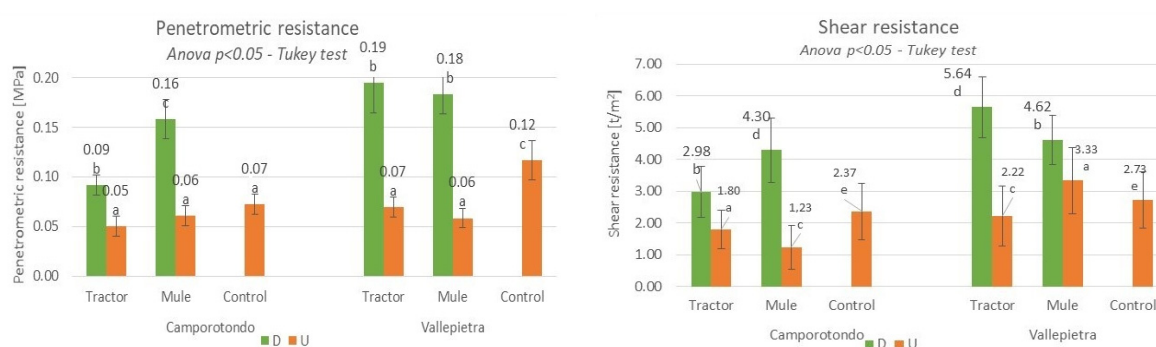

Figure 2. Results of the ANOVA and Tukey's test for penetrometric and shear resistance, which were difference tested among disturbed (D), undisturbed (U), and control soil for the two mechanization levels. Different letters after means within each mechanization level indicate significant differences obtained by Tukey's test ($p < 0.05$).

The statistical analysis on the soil pH values shows a lack of any significant difference between the treatments and site. The measured values define the acidity of the soil and range between 4.4 and 5.8.

In the analysis of the soil disturbance due to logging activities, the content percentage of organic matter present in a control site not affected by forest operations and within the areas affected by the various management systems was analyzed in disturbed and undisturbed areas, respectively (Figure 3).

Analyses were performed separately for both locations. From the data collected in Figure 3, it can be seen that the organic substance content in the Camporotondo area is lower in the disturbed areas than in the undisturbed ones. The undisturbed soil of the site extracted by tractor has a percentage of organic matter very close to the values found in the disturbed soil extracted by mules and in the control area.

The locality of Vallepietra, on the other hand, shows the highest organic matter content was found in undisturbed soils and in the control area with values that are almost similar to each other. For both areas, it is possible to state that extraction has negative impacts on OM content with no substantial difference between the use of tractor or mules.
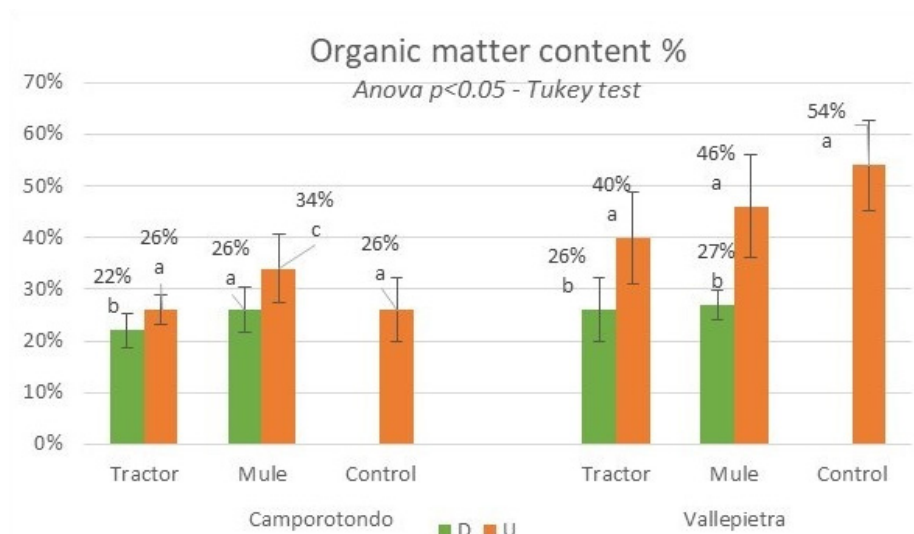
Figure 3. Results of the ANOVA and Tukey's test for Organic matter content (OM), which were difference tested among disturbed (D), undisturbed (U), and control soil for the two mechanization levels. Different letters after means within each mechanization level indicate significant differences obtained by Tukey's test ($p < 0.05$).

By analyzing the samples taken within the areas under study, it was possible to evaluate the impact caused by forest logging on the community of soil micro-arthropods. Statistical analyses on the QBS-ar index values showed statistically significant differences between the different situations analyzed (Figure 4). In both areas, as can be seen from Figure 4, higher QBS-ar values were found in undisturbed soils. The disturbed soil of both sites analyzed shows lower and similar values.

However, the value closest to the QBS-ar found in the Camporotondo control zone is that recorded in the undisturbed soil of the area extracted by mules. The value of the QBS-ar Index also varies significantly for the area located in Vallepietra. In particular, the disturbed soils of both sites (tractor and mules) always show lower density values than the undisturbed and control soils. The highest QBS-ar value was found in the Vallepietra control area.
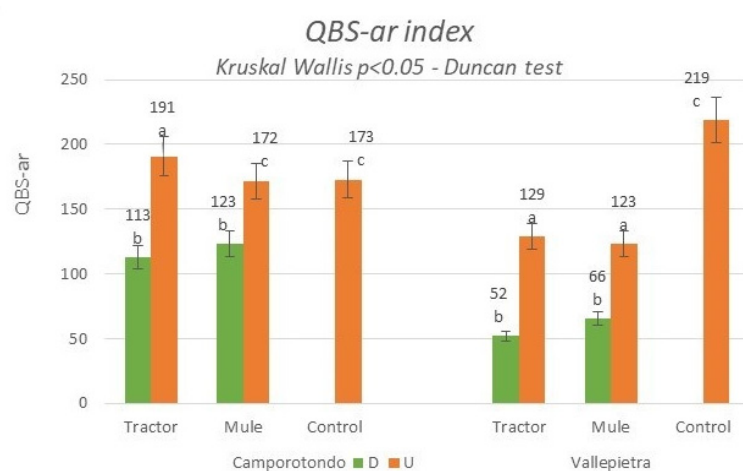

Figure 4. Results of the non-parametric ANOVA and Tukey's test for QBS-ar index, difference tested among disturbed (D), undisturbed (U), and control soil for the two mechanization levels. Different letters after means within each mechanization level indicate significant differences by Tukey's test ($p < 0.05$).

4. Discussion and Conclusions

To have a more accurate understanding of the levels of disturbance that characterize the areas under study, it is useful to carry out a comparative analysis that allows us to highlight the impacts resulting from sylvicultural treatments (mainly referred to soil conditions). These should be applied as a whole to be able to understand in detail the single effect caused by canopy cover reduction on forest operations (both soil and remaining stand conditions).

The displayed nMDS analysis (Figure 5) refers to all significant physical, chemical, and biological soil and subsoil parameters and summarizes the complex situation. The impact caused by sylvicultural treatment is clear for both areas and for both extraction systems, mainly in the Vallepietra site. It does not seem to be clear what the differences are between the use of the tractor and the mule. The impact due to sylvicultural treatment seems minimal for both sites and for both extraction systems. In general, no significant difference in impact soil and topsoil was found between extraction with mules and with a tractor.
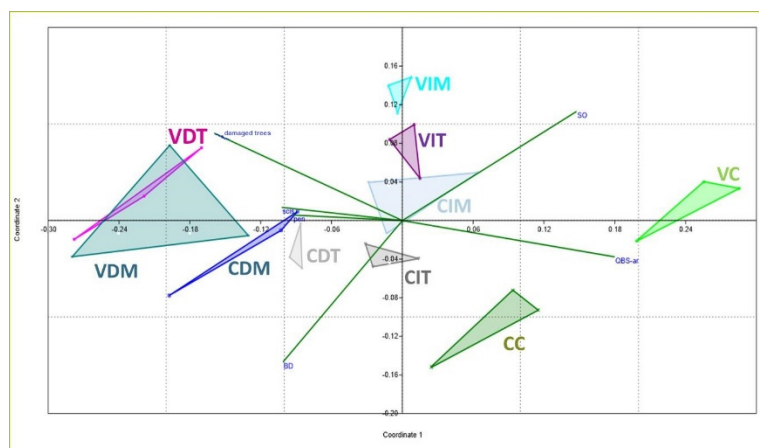

Figure 5. Results of the nMDS analysis refer to all significant physical, chemical, and biological soil parameters and damaged trees and summarize the complex situation. Difference tested among disturbed (Vallepietra Disturbed extracted by Tractor: VDT; Vallepietra Disturbed extracted by Mules: VDM; Camporotondo Disturbed extracted by Tractor: CDT; Camporotondo Disturbed extracted by Mules: CDM), undisturbed (Vallepietra Undisturbed extracted by Tractor: VIT; Vallepietra Undisturbed extracted by Mules: VIM; Camporotondo Undisturbed extracted by Tractor: CIT; Camporotondo Undisturbed extracted by Mules: CIM), and control (Vallepietra Control: VC; Camporotondo Control: CC), for the two mechanization levels in the two areas.

4.1. Applied Sylviculture

With regard to the assessment of the impact of silvicultural management, the percentage variation of the various parameters monitored for undisturbed soil types was considered based on data relating to control areas. It is evident that the disturbance induced is concentrated mostly in the Vallepietra sites affecting both sites (tractor and mules) with a decrease in the percentage of organic matter and inorganic carbon and an increase in bulk density.

Statistical analyses on the QBS-ar index values showed statistically significant differences between the different situations analyzed in this study. It is clear that the micro-arthropods reply to the variation in tree cover which brings out negative variations, resulting in a negligible decrease in the QBS index but only for the Vallepietra sites. This result at ground level can also be considered in terms of the diversity of the structural composition of the soil, both in terms of grain size and stability of the aggregates.

4.2. Forest Operations

The soil disturbance due to forest operations is evaluated as a percentage variation of the data of the disturbed soil strata of each area as compared to the corresponding undisturbed soils. The disturbance level is evident, especially for the soil physical characteristics, which are clearly altered. The same situation was found in all the sites analyzed.

The most impacted sites respectively were the area extracted by mules for Camporotondo and the area extracted by tractor for Vallepietra.

In the processing of the data of the variations of the physical-mechanical characteristics of the soil, it was perceptible that in general, the forest operations and in particular bunching and extraction carried out both with mechanical means and with animals affect the forest soil, causing evident impacts [34–36].

In the context of this study, the pH parameter does not seem to have undergone any significant influence from forest operations, while the organic matter content appears to be lower in the disturbed areas. This is probably due to the loss of the first layers of horizon A due to the passage of animals and vehicles in carrying out operations.

It is also evident how the forest operations have caused an impact on the biological quality of the soil, leading to the reduction of the edaphic component that is most suitable for life in the soil. The areas of disturbed soil underwent a more serious impoverishment than those of undisturbed soil, but in any case, both showed a biological decrease as a result of forest operations.

The results of this study concerning stand damage, indicated a range of 32–46% of residual trees which were damaged by logging activities in the studied areas. This amount of damage to residual trees is considerable if compared with other situations, for example residual tree damage following selection cutting in the Caspian forests ranged between 15% and 20% [37–40]. There are no significant differences when comparing the data of this study with other Italian situations with more similarities (20–56%, Bertolotto et al. [24]). Differences in the percentage of damage are probably due to ground slope and harvesting intensity.

The results of this study showed 85% of wounds occurred at the height of less than 1 m from the ground level on the boles of residual trees. This finding was supported by researchers by Bettinger and Kellogg [41], Solgi and Najafi [42], Lotfalian et al. [37], Naghdi et al. [38], Nikooy et al. [39], Jourgholami [43], and Marchi et al. [33]. The highest risk for decay was given for trees with injuries in the area of the felling cut and the root collar. Our results indicated that 91% of residual trees were damaged with injury sizes <50 cm^2 and mainly related to bark level. The residual trees in these conditions have the capacity to repair these wounds [44].

4.3. Conclusions and Comments

Even when applying silviculture, it must be recognized that it is impossible not to cause damage to the forest ecosystem. Nonetheless, it must be repeated and emphasized that it is necessary to minimize and promptly remedy these anthropogenic disturbances.

Our findings have demonstrated that in silvicultural treatments, the methodologies of felling, processing, and extraction have to be planned on a larger scale. They cannot be sporadic events. They must be connected to the social, environmental, and economic contexts.

In the previous chapters, the problem related to the disturbances due to sylvicultural treatment and logging activities has been shown to be addressed. However, the types of damage found are not attributable exclusively to a single factor, as has been seen. In fact, even if the damage is largely caused by the work systems employed, other aspects should not be overlooked. One of these factors is certainly the ability of the operators who are carrying out the works; in fact, there must be a specialization of workers able to operate while causing the least possible damage. This is especially applicable in the case in which

"primordial" levels of mechanization are adopted where the expertise of the operators always represents a good 50% of the sustainability of the interventions [45].

It has therefore been seen that the impacts that were caused to the soil and forest stands were essentially caused by bunching and extraction operations. The importance of avoiding the continuous passage of vehicles and pack animals on forest soil clearly emerges, especially in conditions of high soil humidity. It is also important to use machines and equipment of a size and performance commensurate with the logging typologies, which are equipped with all the accessories essential for proper work performance [45].

Finally, it can be stated that from the comparison made between the values relating to the impacts assessed in other case studies [46,47] and the impacts found in the Camporotondo and Vallepietra parcels, no significant differences were found, despite having applied different levels of mechanization. However, it remains clear how the correct use of the forest winch can lead to a decrease in the amount of impact on the ground and on the forest stand. This is obtainable, provided that adequate and proper logging operations have been previously planned during the felling operations.

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