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Mediterranean beech forests: Thinning and ground-based skidding are found to alter microarthropod biodiversity with no effect on litter decomposition rate

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ABSTRACT

Despite the high ecological value of Mediterranean beech forests, very little is known about the implications of forest operations on soil microarthropod biodiversity and litter decomposition rate. There is also no information concerning the amount of time needed for disturbed forest soil to recover and return to the pre-harvesting conditions. Silvicultural treatments are scheduled about every ten to fifteen years, without taking into account the amount of time necessary for recovery. The purpose of this study was to determine this information. The study started by selecting three study sites located along the Italian Apennine, each including a chronosequence of three forest parcels: one harvested in 2021, one harvested in 2012, and a control parcel which had not been harvested within the last forty years. In the harvested parcels we investigated skid trails which are classified as disturbed, and soil not affected by the passage of a machine which is classified as undisturbed. Thus in each study area there were five experimental treatments including the control area. The soil physico-chemical properties were assessed for each treatment. These included bulk density, penetration resistance, shear resistance, organic matter content, and soil microarthropod biodiversity which was assessed by the QBS-ar index (Soil Biological Quality based on microarthropods, a qualitative index measuring the quality of soil according to the biodiversity of the microarthropod community). We further established a litter decomposition experiment, using teabags as reference material, to check the differences among treatments in litter decomposition rates. We used linear mixed-effects models to investigate the effects of the experimental treatment on the physico-chemical and biological features, and relationships among QBS-ar index and soil physico-chemical features. We analysed the effects of the experimental treatment on the litter decomposition rate using generalised linear-mixed effects models. A significant effect caused by machine passage was found in the recently harvested parcels on soil penetration resistance (~+70 % comparing to the control), shear resistance (~+35 %), and QBS-ar index (-25 %). Effects of machine passage on soil bulk density and organic matter content were not significant. All the investigated variables in the skid trails returned to values similar to those recorded in the control after ten years. We did not find effects of any soil physico-chemical features on QBS-ar index. Finally, no effect of the experimental treatment was found on the litter decomposition rate, suggesting that a stronger magnitude of soil

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disturbance is needed to affect this complex biogeochemical process. Although the initial impact was highly significant, it was found that a 10-year period is sufficient for recovering the investigated soil features in the upper soil layer. This was observed in Mediterranean beech forests when forest operations were done with low-weight machines and a limited number of machine passes on the skid trails. Thus, it can be concluded that planning another operation 10–15 years after the previous thinning, as is currently done, remains in line with the time needed for the forest soil to recover.

1. Introduction

European beech (*Fagus sylvatica* L.) is a fundamental tree species for European forest ecosystems (Antonucci et al., 2021; de Tomás Marín et al., 2023; Vančura et al., 2022). Beech plays a fundamental role in the European forest sector, secondary only to Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.). Beech is one of the most extensively studied European tree species, owing to its broad distribution and significant ecological and economic value (Antonucci et al., 2021). The species thrives in a variety of environments, ranging from Atlantic to continental climates and the Mediterranean zone, and from moderately dry to periodically wet soils (Caudullo et al., 2017). Consequently, beech forests span over 11 million hectares across Europe. Its natural range extends from southern Scandinavia to southern Italy, and from Spain in the west to Romania in the east (Caudullo et al., 2017). In central Europe, beech is a key component of lowland forests, whereas in the Mediterranean region, it is typically found in mountainous areas, often marking the timberline (Calderaro et al., 2020; Cudlín et al., 2017).

On the Italian peninsula, beech is the dominant species along the Apennines, with almost pure stands that occupy high mountain areas ranging from 1000 to 2000 m a.s.l. (Calderaro et al., 2020; Nocentini, 2009; Nocentini et al., 2022). The usual silvicultural method used for managing beech forests in Europe (Borz et al., 2015; Stoilov et al., 2021; Thom et al., 2020), is the shelterwood method (Latterini et al., 2024b). This method applies the establishment cut when the stand reaches the age of about 100 – 120 years. Prior to the establishment cut different thinning treatments (Trentanovi et al., 2023) are carried out starting from an age of about 80 years (Nocentini, 2009; Paffetti et al., 2012). The most commonly applied harvesting system in thinning and shelterwood cuttings is the Tree-Length System (TLS). This includes felling and preliminary wood processing by chainsaw and extraction of the stems by forestry-fitted tractor equipped with a winch (Latterini et al., 2023b). Dedicated forest machinery, such as skidders and forwarders, are rarely used in Mediterranean forest logging. This is due to the fact that most logging companies are small and cannot afford this type of machinery (Cataldo et al., 2020).

Harvesting operations in these stands are particularly challenging from the point of view of sustainability. This is due to the high ecological importance of Mediterranean beech forests and to the harsh mountainous topographic conditions.

Forest operations in mountainous conditions with steep slopes and substantial terrain roughness are particularly difficult. The highest level of soil disturbance generally occurs when ground-based forest operations are performed on slopes over 20 % (Latterini et al., 2023d; Naghdi and Solgi, 2014). Furthermore, recent studies suggest that the application of a ground-based mechanised harvesting system causes the highest level of soil disturbance, especially when the medium-mechanisation level is applied (Nazari et al., 2021). Medium mechanisation level consists of using mechanised means which are not specifically developed for forest activities (Latterini et al., 2023d; Nazari et al., 2021), as observed during harvesting operations in Mediterranean beech forests. Agricultural machinery used for forest operations has indeed a weight similar to skidders and forwarders, but with higher ground specific pressure and without technical adjustments that limit soil disturbance, e.g. bogie track, auxiliary axles, or large tires (Edlund et al., 2013; Engler et al., 2021; Seixas and McDonald, 1997).

Safeguarding forest soil is one of the most important aspects of sustainable forest operations (Latterini et al., 2024a; Nazari et al., 2023; Shah et al., 2022). During ground-based forest operations, a certain degree of soil compaction and displacement is unavoidable, but it can be mitigated with specific best management practices (Labelle et al., 2022; Latterini et al., 2024c; Nazari et al., 2024). Despite the importance of beech forests in Mediterranean forestry, the topic of logging disturbance to the forest soil in this kind of stands has been emphasized mostly in other areas of the globe, for instance in Iran, and focused on different silvicultural methods, namely single tree or group selection (Jourgholami et al., 2019b; Sohrabi et al., 2021). The more recent studies that focused on soil disturbance in Mediterranean beech forests were conducted by our research group. In a case study in Mount Amiata (Tuscany, Italy) we found strong soil compaction in the skid trails, with values of bulk density that increased by about 50 % in comparison to the soil which was not affected by the passage of a machine (Venanzi et al., 2022). Mechanical soil disturbance also led to decreased biodiversity of soil microarthropods in the skid trails, with a 22 % decrease in the QBS-ar (soil biological quality index based on the microarthropod biodiversity) (Venanzi et al., 2022). In another study done in beech forests, the short-term (less than two years after harvesting) soil disturbance caused by forest operations was assessed in different skid trails. The study revealed that alterations of soil physico-chemical properties such as bulk density, penetration resistance, shear resistance, and soil organic matter were comparable to the those which occurred during coppicing of Turkey oak (*Quercus cerris* L.) and chestnut (*Castanea sativa* L.), when applying similar harvesting systems (Latterini et al., 2023d). However, what is missing from these studies is the evaluation of the recovery time after harvesting, as both studies presented short-term evaluations, i.e. maximum two years after harvesting. Thus, for the Mediterranean beech forests there is no scientific information about the soil recovery time needed to re-establish the pre-harvesting conditions. The recovery time is not known, and thus it cannot be determined if this is acceptable for the established schedule for logging entries every 10 – 15 years.

Soil disturbance related to forest operations goes beyond mere soil compaction, also affecting biogeochemical soil processes such as litter decomposition (Latterini et al., 2023a). On the one hand, compacted soil might raise temperatures, thus accelerating the rate of decomposition (Kranabetter and Chapman, 1999). On the other hand, reduced rates of decomposition may result in disruptions associated with the removal of organic matter and changes in the edaphic communities of the soil (Enez et al., 2015). A recent meta-analysis study focused on the influence of silvicultural treatments and forest operations on litter decomposition rate, highlighted that only a few studies investigated how the establishment of skid trails alters the process of decomposition (Latterini et al., 2023a). In this regard, Enez et al. (2015) noted the influence of soil disturbance magnitude in slowing down the litter decomposition rates. In fact, they reported a significant drop in scalped soil as consequence of bunching-extraction operations performed by a farm tractor equipped with a winch. In contrast, other studies stated that soil compacted by the passage of crawler tractors or excavators did not reveal substantial alterations in the litter decomposition rate, when compared to the soil not affected by the passage of machines (Kranabetter and Chapman, 1999; Yoshida et al., 2019). Therefore, there is currently no information on how and to what extent forest operations in beech forests can alter the litter decomposition process in the skid trails.

Considering these facts and details, we developed this study to investigate the disturbance caused to Mediterranean beech forests soil by mechanised ground-based forest operations and the recovery time after harvesting. This study focused on both physico-chemical and biological (microarthropod biodiversity) upper soil properties as well as on litter decomposition rate. We hypothesised that: i) the passage of forest machinery along the skid trails alters both the physico-chemical and biological soil properties in the short-term; ii) considering the low canopy alteration related to thinning treatments, disturbance to the soil not affected by passage of the machines is not significant; iii) a 10-year period is enough to restore the physico-chemical and biological features of the soil disturbed by passage of the machines; iv) alteration to the soil microarthropod community in the skid trails is directly related to alteration of the soil physico-chemical features; v) the decomposition process in the skid trails is significantly slowed down in the short-term but returns to the pre-harvest conditions in a 10-year period.

2. Materials and methods

2.1. Study areas

We identified three study areas along the Italian peninsula (Fig. 1A), one in the Central-North (Area 1 – Mount Amiata), one in the Central-South (Area 2 – Simbruini), and one in the extreme South (Area 3 – Aspromonte Massif). Each area consists of a chronosequence made up of three forest parcels, one harvested in 2021 (NEW), one in 2012 (OLD), and one unharvested for at least 40 years (control area– CON). All the forest parcels consist of even-aged beech forests in which beech represents more than 90 % of the total basal area, as well as sporadic individuals of *Acer pseudoplatanus* L., *Sorbus aucuparia* L. and *Abies alba* Mill. which were identified in the stands. In all the parcels harvested in 2021 or 2012, the same harvesting system was applied, consisting of the Tree-Length System with felling and processing by chainsaw followed by extraction with a forestry-fitted tractor equipped with a winch (Fig. 1B). All the interventions consisted of thinning from below with a maximum harvesting intensity of 35 % of the standing volume. Area 1 is located in Mount Amiata, a vulcanic massif located in the Tuscany region not directly belonging to the Apennine, average annual rainfall is 1554 mm, with an average annual temperature of 9 °C (Table 1). The bedrock is volcanic and soil type in the three investigated forest parcels from this area can be classified as Cambisol, with a sandy-loam soil texture. Area 2 is located at the border between the Latium and Abruzzo regions, average annual rainfall is 1600 mm, with an average annual temperature of 11 °C. The bedrock is limestone and soil type in the three investigated forest parcels from this area can be classified as Leptosol, with a silty-clay soil texture. Area 3 is located in the Calabria region, average annual rainfall is 1611 mm, with an average annual temperature of 14 °C. The bedrock is metamorphic and soil type in the three investigated forest parcels from this area can be classified as Umbrisol, with a sandy soil texture.

The soil in the harvested parcels (both NEW and OLD) was separated into undisturbed (UND – not affected by the passage of a machine) and disturbed (DIST – affected by the passage of a machine) areas. According to Latterini et al. (2023d), a comparison of disturbed and undisturbed/control soil provides insight into the disturbance caused by a machine's passage, while the degree of disturbance associated with the applied silvicultural treatment can be determined by comparing the undisturbed soil to the control area. Applying the same design to forest parcels harvested in different years allowed for the evaluation of the recovery process of soil features. The 10-year interval was selected as it represents the minimum time that generally occurs between two consecutive interventions, within the shelterwood method in the study areas. In this way, our experimental design consisted of five experimental treatments: DIST_NEW, DIST_OLD, UND_NEW, UND_OLD, and CON. It is important to highlight that we focused our analysis on secondary and tertiary skid trails established during the harvesting operations, thus on skid trails that experienced a limited number of machine passes, ranging from one to ten passes (DeArmond et al., 2021). Primary skid trails affected by a higher number of machine passages were not present in any of the investigated parcels. It is important to consider that the loggers used as primary extraction routes the pre-established forest road network, which are very common in Mediterranean beech forestry.

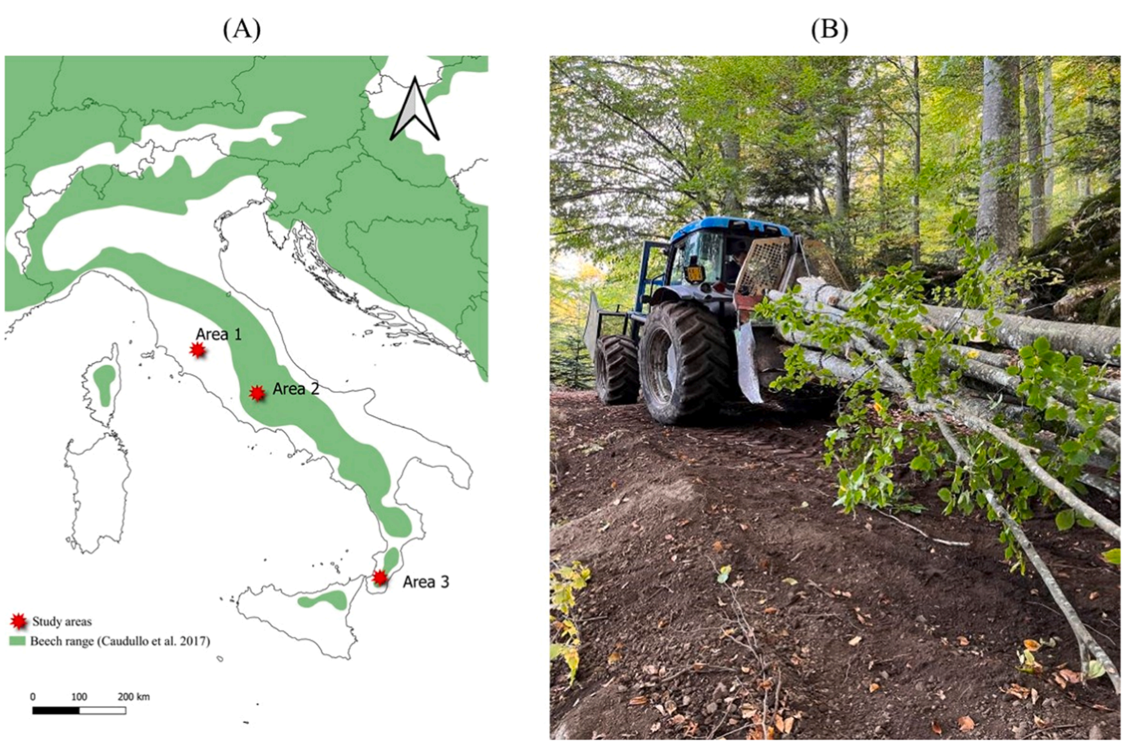

Fig. 1. (A) Locations of the study areas. (B) Forestry-fitted tractor equipped with a winch while skidding beech stems along a pre-established forest road in Area 1 – photo by Authors.

Table 1
Main features of the study areas.

Parameter	Area 1 – Mount Amiata			Area 2 – Simbruini			Area 3 – Aspromonte Massif		
	NEW	OLD	CON	NEW	OLD	CON	NEW	OLD	CON
Average annual temperature (°C)	9			11			14		
Average annual rainfall (mm)	1554			1600			1611		
Bedrock type	Volcanic			Limestone			Metamorphic		
Soil type	Cambisol			Leptosol			Umbrisol		
Soil texture	Sandy-loam			Silty-clay			Sandy		
Harvesting year	2021	2012	none	2021	2012	none	2021	2012	none
Age at harvesting	95	96	92	85	87	85	80	82	80
Prevalent slope (%)	27	31	30	29	32	32	10	12	20
Terrain roughness[a]	I class	II class	I class	II class	II class	II class	I class	I class	I class
Harvesting intensity[b](%)	28	26	-	22	20	-	28	28	-
Tractor mass (kg)	5700	5700	-	5400	5400	-	5700	5700	-

[a] I class: obstacles to the movement of ground-based machinery on less than 20 % of the total surface of the parcel; II class: obstacles to the movement of ground-based machinery on 20 – 40 % of the total surface of the parcel.
[b] Harvesting intensity expressed as a percentage of the total standing volume before harvesting

The established secondary and tertiary skid trails are closed to off-road traffic after harvesting, thus we can exclude the potential for impacts of any machines different from the tractor that established the trails trafficked beneath them.

2.2. Preliminary analysis

Before evaluating the features of the soil, we calculated the proportion of disturbed soil (DIST) relative to the overall surface of the forest parcel. To conduct this study, four linear transects (1 × 50 m) were established in each harvested parcel using a tape measure and compass. The transects started from a randomly selected point within the parcel, and then followed North, South, West and East directions respectively. Along the transect, visual inspection was employed to identify disturbed from undisturbed soil by checking for indications of crushed litter, ruts, or soil mixing. Subsequently, the detected disturbed surface was reported as a percentage of the overall area of the transect. In the harvested forest parcels, the percentage of disturbed soil varied between 24 % and 31 %. The disturbed surface was still recognisable also in the parcels harvested 10 years before the surveys, also thanks to the presence of stumps, wounded trees and with the help of local forest engineers who supervised the logging operations at the time of harvesting.

2.3. Soil physico-chemical and biological features

Soil surveys were conducted in November 2022 in all three study areas. Therefore 10 years after harvesting in the OLD parcels and 1 year after harvesting in the NEW parcels. Using a specialised corer, six soil samples were taken for each experimental treatment, collecting 30 soil samples per study area and 90 in total, to estimate the bulk density to a 5 cm depth (g cm^{-3}). After being sealed in plastic envelops, the samples were taken to the lab. Following oven drying at 105 °C to constant weight (dry weight), soil samples were then weighed. The value of soil bulk density was determined by dividing the dry weight by the volume of the cylinder of the corer (100 cm^3) (Page-Dumroese et al., 1999). Dedicated handheld instruments were used to assess the shear resistance (Mg m^{-2} - the magnitude of the shear stress that a soil can sustain) and penetration resistance (MPa - the force required to move a specially-tipped metal rod through the soil) in the top 5 cm of soil. According to Saxton et al. (1986), the obtained values were then referred to the soil water-holding capacity. The same number of measurements as for bulk density were taken for both shear resistance and penetration resistance.

Six soil samples (30 per study area, 90 in total) were taken for each experimental treatment using the bulk density corer to calculate the percentage of organic matter in the soil. After that, the amount of organic matter in the soil was calculated after combustion for 4 h at 400°C in a muffle incinerator (Rosell et al., 2001).

The disturbance to the biological component of the forest soil was evaluated using the QBS-ar index. This is a qualitative index which assesses the biodiversity of the microarthropod community in the soil. The fundamental idea behind this measure is that a high concentration of microarthropod groups which are specifically adapted to the soil environment is indicative of high-quality soil (Parisi et al., 2005). As soil microarthropods have adapted their morphology to the soil environment, they can be classified into a variety of biological types. Each form is given an EMI (ecomorphological index) score, which varies from 1 to 20 according to the degree of adaption (Parisi et al., 2005). Subsequently, the QBS-ar index is computed by summing the EMIs for each group in a specific soil sample. Six soil samples per experimental treatment (30 per study area, 90 in total), each measuring 10 × 10 × 10 cm, were used to calculate the QBS-ar index. After shipping the samples to the laboratory, the microarthropods were removed from the soil samples using Berlese–Tüllgren funnels. The various specimens in each sample were preserved in a solution (75 % ethyl alcohol and 25 % glycerol by volume) and then classified at different taxonomic levels (order for Insecta, Collembola, Chelicerata, and Crustacea, and class for Myriapoda) using a stereo microscope.

It is important to mention that the sampling of soil bulk density, penetration resistance, shear resistance, soil organic matter, and QBS-ar took place in the same places for each experimental treatment, allowing us to develop specific models relating the variables.

2.4. Litter decomposition rate

For the evaluation of litter decomposition rate we decided to use two types of tea as reference material, namely green tea and rooibos tea (Keuskamp et al., 2013). The teabag method for the evaluation of decomposition rate is an innovative, cost-effective, and standardised method, which uses two different types of tea which decompose at different rates. Green tea is a fast decomposing tea type, while rooibos tea is more recalcitrant to decomposition (Keuskamp et al., 2013). Furthermore, the teabag method was also developed to shorten the duration of the experiment, which with common litterbag experiment can last several years.

We made and labelled mesh bags measuring 15 cm×15 cm. These were made from 1 mm mesh fibreglass netting. One oven-dried green teabag and one oven-dried rooibos teabag were placed into each mesh bag after weighing them to know the initial mass. These mesh bags were installed in June 2023 and collected at 5, 13, and 22 weeks after the installation in every study area. Installation was carried out as follows: in every study area for every experimental treatment (DIST_NEW, DIST_OLD, UND_NEW, UND_OLD, CON), we identified five places which we identified as replication ID. The mesh bags were tied with a nylon cord to standing beech trees on the skid trails (disturbed treatments), on the soil not affected by the passage of a machine (undisturbed treatments), and in the control area. The total number of teabags installed was: 3 study areas x 5 experimental treatments x 3 collection times x 2 tea types x 5 replication IDs, corresponding to 450 teabags (225 mesh bags containing one green teabag and one rooibos teabag each).

During the collection each mesh bag (containing one green teabag and one rooibos teabag) was immediately packed into an envelope on the field so as to prevent any material loss. Any trace of invading material such as sand, insects, or flora was eliminated by sorting with tweezers under a dissecting microscope and then the teabags were oven dryed for a minimum period of 72 hours. Each teabag was then weighed on a 0.001 g precision scale. This allowed for the calculation of the loss of mass in the tea.

2.5. Statistical analysis

To investigate the effects of the experimental treatments on soil physico-chemical features and QBS-ar index we used linear mixed-effects models (LMMs), using the experimental treatment as a fixed effect and the study area as a random intercept. The random intercept of the model allowed us to account for the spatial dependence of data collected within the same study area. We used the packages lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) implemented in the R software (R Development Core Team, 2023). We presented the results using analysis of variance (ANOVA) and marginal means, i.e. mean predicted values for the global population, excluding random effects (Searle et al., 1980). We used Tukey's posteriori test to group the mean values of treatments. For marginal means calculation and posteriori tests we used the emmeans package (Lenth et al., 2019). We also investigated the relationships between QBS-ar and soil physico-chemical features by applying LMMs. To build the model, the QBS-ar index was indicated as the dependent variable; soil bulk density, penetration resistance, shear resistance, and organic matter were the fixed effects and the study area was indicated as the random intercept. For the developed model we calculated marginal and conditional coefficients of determination (R^2_m and R^2_c), explaining the proportion of variability explained by fixed effects only and by both random and fixed effects, respectively (Nakagawa and Schielzeth, 2013), by using the MuMin package (Bartoń, 2023). We used marginal responses implemented in the ggeffects package (Lüdecke, 2018), representing the mean model outcome for the global population (excluding random effects), to visualise only the fixed effects.

To assess the impact of experimental treatments on tea decomposition we used generalised linear mixed-effects models (GLMMs), implemented in the glmmTMB package (Lüdecke, 2018). Due to the different chemical composition and rate of decomposition of the two types of tea (Keuskamp et al., 2013), we developed a separate GLMM for each of them. In each GLMM we used mass loss (fraction of mass lost during decomposition) as the dependent variable and date (number of weeks of incubation in the field), treatment, and their interaction as independent variables. We assumed the Beta distribution of the response variable, due to its fractional character. We included replication ID (place within study plot) nested in plot identifier as a random intercept to account for sample spatial dependence. We presented the results of GLMMs as response curves for each treatment and time using marginal responses in the ggeffects package (Lüdecke, 2018) and marginal means for treatments estimated using the emmeans package (Lenth et al., 2019) – mean values of each treatment assuming a constant level of all other predictors and no random effect (global estimate). We also reported values of Akaike's Information Criterion, corrected for small sample size for models and null models (models with intercept only and no random effects).

3. Results

3.1. Effect of the experimental treatment on soil physico-chemical features and QBS-ar

Statistical analysis revealed significant differences ($p<0.05$) among the experimental treatments for all of the investigated soil physico-chemical features (Table 2). Surprisingly, bulk density and organic matter did not reveal an effect of machine passage. Indeed, for bulk density the only treatment that differentiated from the others was UND_NEW, which were significantly lower than the control. For organic matter, there seems to be an effect of the forest parcel, with data from the recently harvested parcels higher than the control area and previously harvested ones. Machine passage showed to have a strong effect on the very superficial soil compaction (first 1–2 cm of the soil), revealed by statistically higher values of soil penetration and shear resistance in the DIST_NEW treatment in comparison to the undisturbed soils and control area. Values of penetration resistance and shear resistance in the new skid trails were 75 % and 34.4 % higher than control values, respectively. However, this difference is not evident anymore when considering the DIST_OLD treatment, with values that return in line with those of the control treatment for both the variables. The effects of the silvicultural treatment (thinning from below) were negligible for all the investigated variables, with practically no differences among the undisturbed treatments (UND_NEW and UND_OLD) and the control values.

The disturbances created by the passage of machines were evident in the soil microarthropod community, with QBS-ar values in the DIST_NEW treatment that were significantly lower (about −25 %) than in the other treatments. However, after 10 years QBS-ar index in the skid trails (DIST_OLD) returned to values in line with the control area. Also concerning QBS-ar, the effect of the silvicultural treatment was negligible (Fig. 2).

Table 2
Results of the statistical analysis carried out on soil physico-chemical features.

Experimental treatment	Average	Lower 95 % CI	Upper 95 % CI	Tukey homogeneous group
Soil bulk density (g cm^{-3})				
CON	0.614	0.393	0.835	a
DIST_NEW	0.584	0.363	0.805	a,b
DIST_OLD	0.673	0.452	0.894	a
UND_NEW	0.479	0.259	0.7	b
UND_OLD	0.564	0.344	0.785	a,b
Soil penetration resistance (MPa)				
Experimental treatment	Average	Lower 95 % CI	Upper 95 % CI	Tukey homogeneous group
CON	0.144	0.0229	0.265	b,c
DIST_NEW	0.252	0.1306	0.373	a
DIST_OLD	0.191	0.0695	0.312	b
UND_NEW	0.158	0.0367	0.279	b,c
UND_OLD	0.131	0.0101	0.252	c
Soil shear resistance (Mg m^{-2})				
Experimental treatment	Average	Lower 95 % CI	Upper 95 % CI	Tukey homogeneous group
CON	2.5	0.842	4.16	b,c
DIST_NEW	3.36	1.7	5.02	a
DIST_OLD	2.92	1.259	4.58	a,b
UND_NEW	2.11	0.453	3.77	c
UND_OLD	1.99	0.327	3.65	c
Soil organic matter (%)				
Experimental treatment	Average	Lower 95 % CI	Upper 95 % CI	Tukey homogeneous group
CON	27.9	6.89	49	c
DIST_NEW	31.6	10.55	52.6	a,b
DIST_OLD	27.1	6.07	48.2	c
UND_NEW	33.1	12.06	54.2	a
UND_OLD	29.5	8.43	50.5	b,c

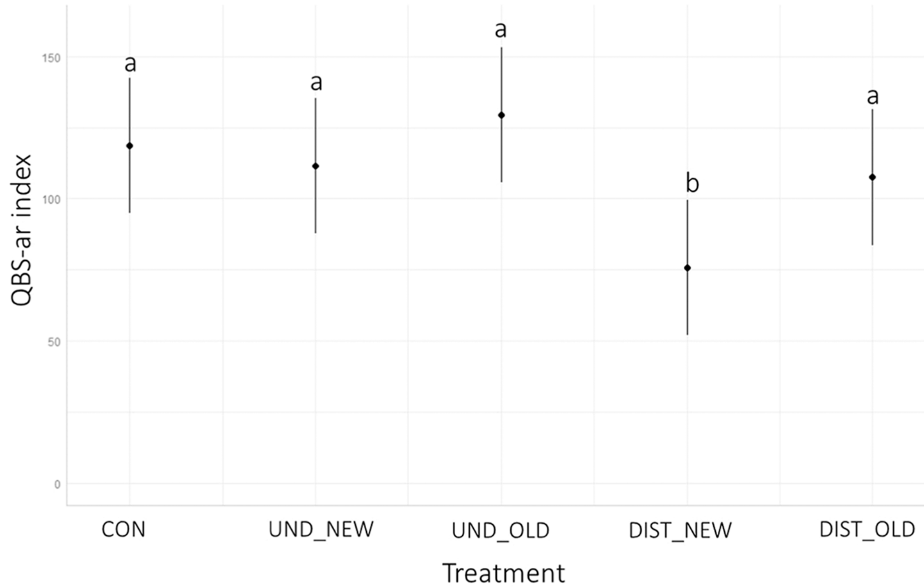

Fig. 2. Values of QBS-ar index in the various experimental treatments. Black dots represent the average value, black lines represent the 95 % confidence intervals, and lowercase letters represent the homogeneous groups according to Tukey posteriori test.

3.2. Effect of soil physico-chemical features on QBS-ar

Surprisingly, LMM models did not reveal a significant effect of any physico-chemical soil feature on the QBS-ar index (Fig. 3), with R^2_m of 0.052 and R^2_c of 0.368 (Table 3).

3.3. Effect of the experimental treatment on litter decomposition rate

Mass loss of the green tea depended on incubation time, while we did not find any impacts of experimental treatments (Table 4, Fig. 4). Mean predicted mass loss after five weeks was 55.9±6.7 %, after 13 weeks

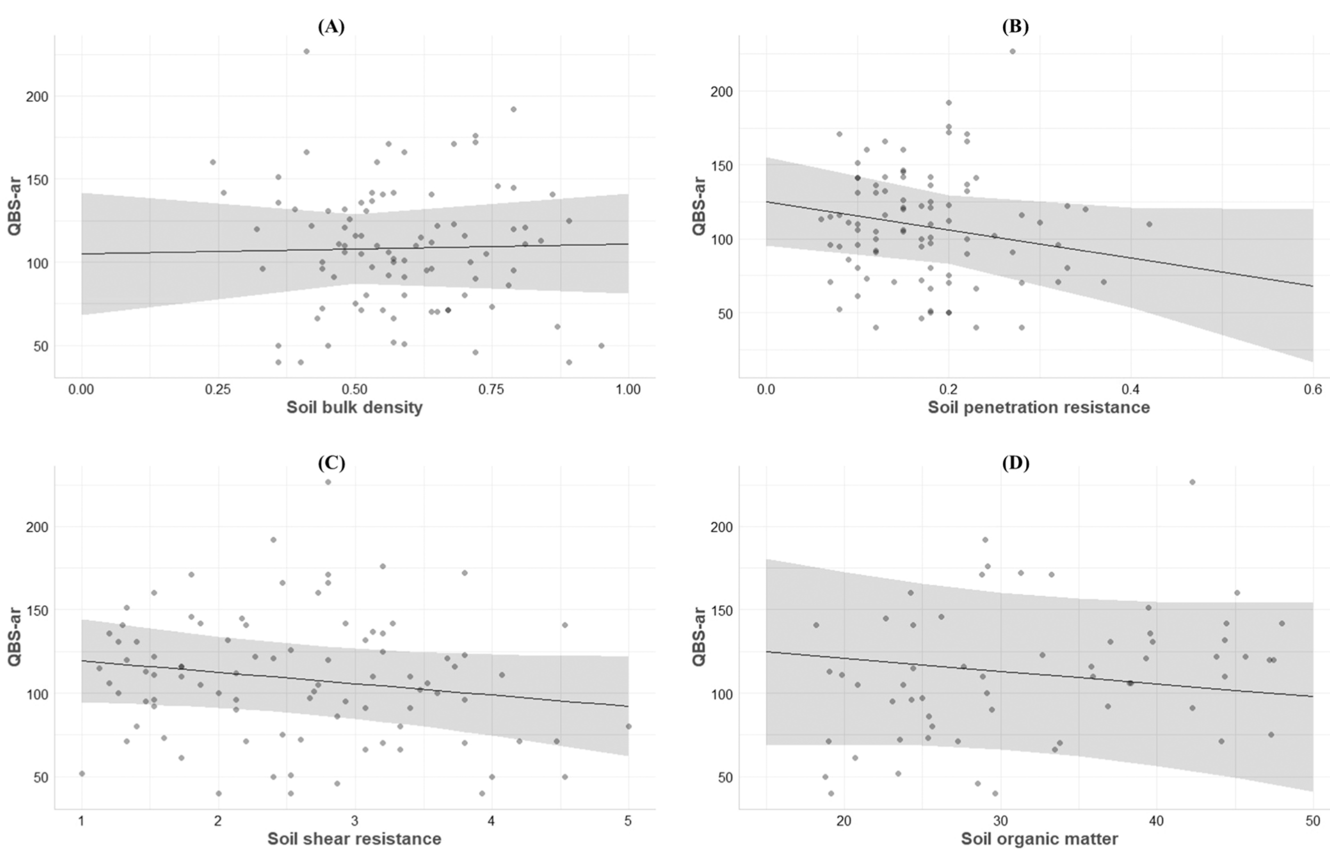

Fig. 3. (A) LMM model QBS-ar vs soil bulk density, (B) LMM model QBS-ar vs soil penetration resistance, (C) LMM model QBS-ar vs soil shear resistance, (D) LMM model QBS-ar vs soil organic matter. Dots indicate data, the black lines are regression lines, and grey ribbons are 95 % confidence intervals.

Table 3
Linear mixed-effects models of QBS-ar.

	QBS-ar			
Predictors	*Estimates*	*Standard Error*	*t value*	*p*
(Intercept)	137.2387	40.8745	3.358	0.00232**
Bulk density	14.1158	29.6144	0.477	0.63483
Penetration resistance	-59.6702	76.6848	-0.778	0.43869
Shear resistance	-4.7653	6.1620	-0.773	0.44148
Soil organic matter	-0.4745	0.9471	-0.501	0.61873
Random Effects				
N area	3			
Standard deviation	34.82			
Observations	90			
Marginal R^2 / Conditional R^2	0.05228506 / 0.368294			

** indicates significant effect at p<0.01

Table 4
Generalised linear mixed-effects models of mass loss in teabags within experimental variants.

Model	Variable	Estimate	SE	z	Pr(>|z|)
Green tea	(Intercept)	0.098	0.080	1.225	0.220
AICc=-695.5	TreatmentDIST_NEW	0.010	0.088	0.113	0.910
$AICc_0$=-568.2	TreatmentDIST_OLD	0.089	0.090	0.991	0.322
Replication in site RE SD=0.033	TreatmentUND-NEW	0.000	0.088	0.001	0.999
Site RE SD=0.086	TreatmentUND_OLD	0.074	0.088	0.845	0.398
	Incubation time	0.028	0.004	6.640	<0.001
	TreatmentDIST_NEW: Incubation time	0.003	0.006	0.425	0.671
	TreatmentDIST_OLD: Incubation time	-0.004	0.006	-0.710	0.478
	TreatmentUND-NEW: Incubation time	-0.001	0.006	-0.157	0.875
	TreatmentUND_OLD: Incubation time	-0.001	0.006	-0.136	0.892
Rooibos tea	(Intercept)	-1.341	0.082	-16.336	<0.001
AICc=-665.9	TreatmentDIST_NEW	0.012	0.109	0.110	0.913
$AICc_0$=-443.7	TreatmentDIST_OLD	-0.104	0.113	-0.924	0.356
Replication in site RE SD=0.042	TreatmentUND-NEW	-0.145	0.111	-1.300	0.194
Site RE SD=0.043	TreatmentUND_OLD	-0.019	0.109	-0.176	0.861
	Incubation time	0.049	0.005	9.845	<0.001
	TreatmentDIST_NEW: Incubation time	-0.004	0.007	-0.563	0.574
	TreatmentDIST_OLD: Incubation time	-0.002	0.007	-0.291	0.771
	TreatmentUND-NEW: Incubation time	0.002	0.007	0.248	0.804
	TreatmentUND_OLD: Incubation time	-0.004	0.007	-0.620	0.535

SE – standard error, z – test statistic, Pr(>|z|) – p-value, AICc – Akaike's Information Criterion, corrected for small sample size, AICc0 – AICc of null (intercept and random effects only) model, RE SD – standard deviation of random effect

61.4±5.8 %, and after 22 weeks 67.2±6.9 %. The maximum difference between treatments was 1.8 % (61.3±1.4 % in UND_NEW versus 63.1 ±1.3 % in UND_OLD), indicating neither statistical nor biological significance of differences among experimental treatments. Mass loss of rooibos tea also depended on incubation time, while we did not find any impacts of experimental treatments (Table 4, Fig. 4). Mean predicted mass loss after five weeks was 25.0±6.2 %, after 13 weeks 33.0±4.4 %, and after 22 weeks 43.3±5.9 %. The maximum difference between treatments was 2.8 % (30.5±0.9 % in DIS_OLD versus 33.3±1.0 % in control), indicating neither statistical nor biological significance of differences among experimental treatments.

4. Discussion

4.1. Effect of the experimental treatment on soil physico-chemical features and QBS-ar

The first hypothesis was that *the passage of forest machinery along the skid trails alters both the physico-chemical and biological soil properties in the short-term*. This hypothesis can be considered confirmed although there are some limitations. We found that in the investigated secondary and tertiary skid trails, established during thinning interventions in beech forests, there is a significant alteration of the investigated soil traits. This is particularly true for the very superficial soil compaction, measurable by penetration and shear resistance (Table 2), and for the soil microarthropod biodiversity (Fig. 2). In contrast, we did not reveal an effect of machine passage on soil bulk density and organic matter content (Table 2). Our previous research on silvicultural interventions in beech forests of the Mediterranean area showed that penetration resistance and shear resistance were particularly sensitive to the passage of the machinery used for ground-based forest operations, with effect sizes considerably higher than that reported for bulk density. Specifically, effect sizes measured as an increased percentage in comparison to the undisturbed soil were about +60 % for penetration resistance and +70 % for shear resistance (Latterini et al., 2023d), which is in line with the values of this study. However, the effect size for bulk density was only about +13 %, although it was significant (Latterini et al., 2023d). Similar effect sizes in terms of increased penetration resistance and shear resistance were also revealed in previous studies in Mount Amiata (Area 1), but in that case we found increased bulk density and decreased soil organic matter along the skid trails, in contrast to what happened in this research (Venanzi et al., 2022). However, this difference can be related to the fact that in the study of Venanzi et al. (2022), the focus of the research was also on primary skid trails, characterised by a higher number of machine passes. Furthermore, the intervention studied by Venanzi et al. (2022) was the second thinning in the investigated parcel, while the focus in all areas included in this study was on the first thinning. This means that before being harvested, the forest parcels in this study had not undergone any silvicultural interventions for decades. In undisturbed beech forests, a thick layer of litter is created due to the slow decomposition rate of beech leaves (Horodecki et al., 2019; Jacob et al., 2010). This litter layer could represent a sort of buffer that protects the soil from the compaction caused by machinery. This can be true for light-intensity interventions such as thinning, due to the dimensions of the machine or the limited number of passes in the investigated parcels. When the weight of the machine, the number of passes and the weight of the extracted load increase, as for example in selection cutting in Iran, the level of soil disturbance can be much higher (Naghdi et al., 2015; Solgi et al., 2017). However, we found that the soil microarthropod biodiversity in the skid trails in parcels harvested in 2021 was significantly lower than that measured in the other experimental treatments. This suggests that ground-based forest operations can be detrimental in the short-term for soil microarthropods, even if light machinery and low harvesting rates are applied.

The second research hypothesis was *considering the low canopy alteration related to thinning interventions, the disturbance to the soil not affected by the passage of the machines is not significant*. This hypothesis was fully confirmed. The soil disturbance related to the silvicultural treatment and assessed by comparing the values of undisturbed treatments with the control values was negligible in the parcels harvested in both 2021 and 2012 (Table 2 and Fig. 2). Previous research also highlighted that canopy alteration and consequent rainfall penetration can trigger a certain degree of soil disturbance, affecting both physico-

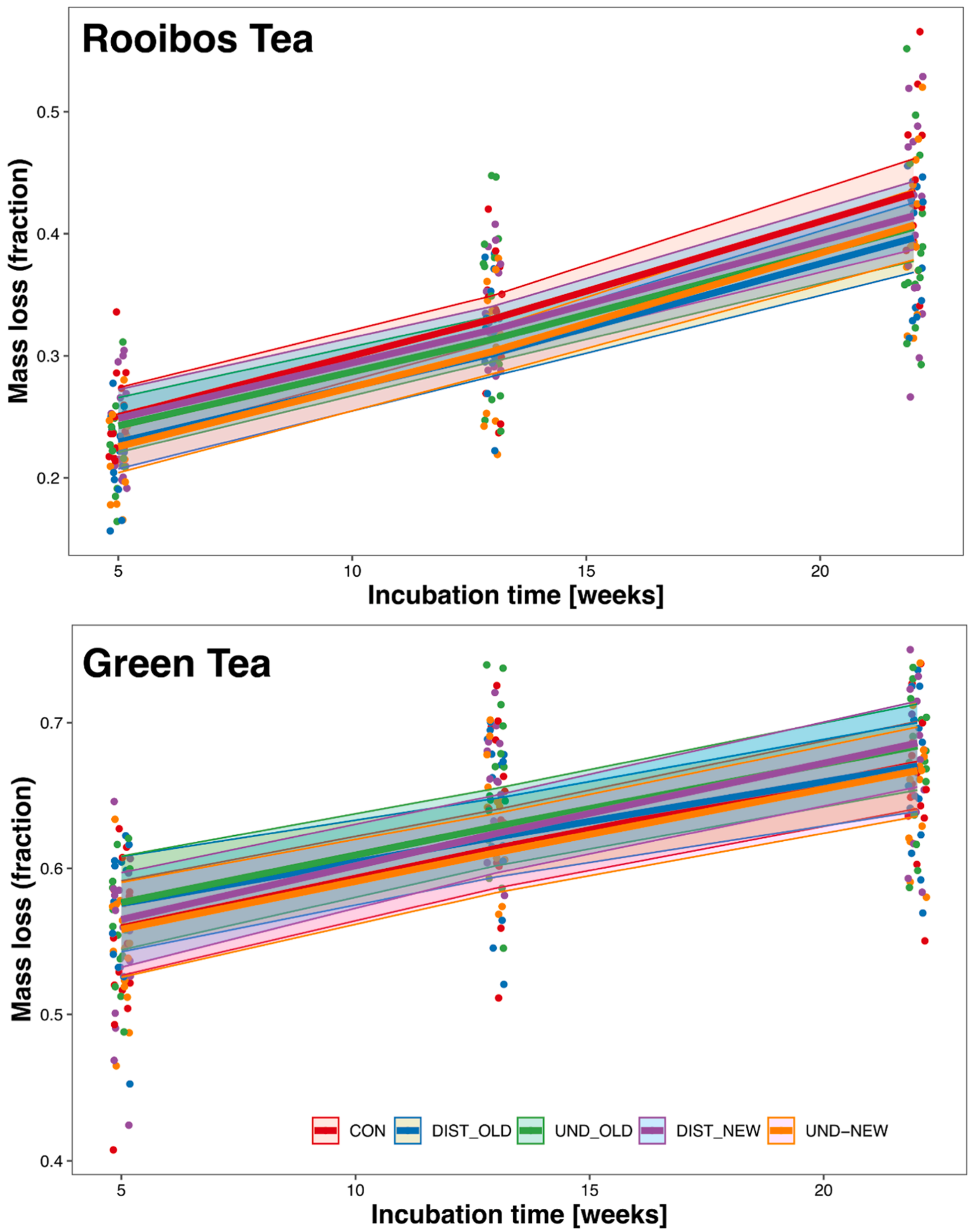

Fig. 4. Mass loss of tea samples in the decomposition experiment at three sampling dates and among five experimental treatments, assessed using Generalised Linear Mixed-effects models (Table 4). Lines and ribbons indicated marginal responses and 95 % confidence intervals, points represent measured values.

chemical and biological features. However, such disturbance was revealed for intervention creating a clear canopy opening, such as group selection, single tree selection (Jourgholami et al., 2021), and coppicing with standards (Venanzi et al., 2019). In the case of thinning from below, the harvesting intensity is at a maximum of about 30 % and the harvest does not involve the dominant individuals. Thus the canopy alteration is light and produces only negligible disturbance to the soil.

The third hypothesis (*a 10-year period is enough to restore the physico-chemical and biological features of the soil disturbed by the passage of the machine*) was fully confirmed as well. The values of all the investigated variables in the skid trails, including soil microarthropod biodiversity, returned to values in line with those of the control and undisturbed soil after 10 years (treatment DIST_OLD – Table 2 and Fig. 2). This is one of the most important findings of this research, concerning the practical implications for forest management. We did in fact reveal that the current silvicultural practice in the study areas, which generally provides a further intervention (another thinning or the establishment cut) in 10–15 years after the previous thinning, is in line with the recovery capacity of the forest soil ecosystem. The evaluation of the recovery time after harvesting is a complex but fundamental aspect that is often lacking in the studies on this topic (Latterini et al., 2023c). Soil features in the skid trails tend to recover, but an increasing amount of time is needed according to the initial magnitude of disturbance. A few years can be enough for secondary and tertiary skid trails such as those investigated in our study (Goutal et al., 2012; Zenner et al., 2007), but a much longer time is needed for the heavily disturbed primary skid trails and landing sites (DeArmond et al., 2024, 2022, 2019). In our case, the short recovery time is probably related to the low initial disturbance and to the alternation of freeze and thaw, wet and dry periods that characterises the Apennine zone (DeArmond et al., 2021). The role of bioturbation (the alteration of soil structure caused by biological agents like plants and animals) in the skid trails recovery (Bottinelli et al., 2014) can be mostly excluded in our case, considering that the presence of both tree regeneration and herbaceous species were practically absent in the investigated skid trails and therefore the recovery process cannot be attributed to root development.

4.2. Effect of soil physico-chemical features on QBS-ar

The fourth research hypothesis formulated in our study (*the alteration to soil microarthropod community in the skid trails is directly related to the alteration of the soil physico-chemical features*) was rejected. We did not find any significant relationship among soil physico-chemical features and QBS-ar index (Table 3 and Fig. 3). The few previous studies that investigated the presence of this kind of relationships revealed a decreasing QBS-ar index in soil at high bulk density (Blasi et al., 2013; Latterini et al., 2023d). From our results, it seems that the disturbance to the soil microarthropod community is related to more complex interactions among the machine impacts, the micro-climate conditions, the light exposure and the soil, than to mere compaction. Apart from compaction the other possible alterations that can immediately occur after the establishment of a skid trail on the forest soil are soil displacement, rutting (which is however strongly related to compaction), and removal of the litter layer (Jourgholami et al., 2019a; Marra et al., 2022). In our cases, in the investigated secondary and tertiary skid trails, soil displacement and rutting were not present, thus excluding these two factors from the possible causes of the disturbance to the soil microarthropod community. Litter removal was instead evident in the DIST_NEW treatment, although not directly measured in our experimental design, thus we suggest that future studies on that topic should also consider this variable. It is worth highlighting that the QBS-ar index does not account for the number of soil microarthropods but only for the presence or absence of specific taxonomic groups. It is possible that, although not directly related to a decrease in the QBS-ar index, the alteration linked to the passage of the machine on the physico-chemical features of the soil could show a stronger response when going deeply into the details of microarthropod biodiversity, for instance when checking the number of individuals or the biodiversity of specific taxonomic groups at a more detailed level (Díaz-Aguilar et al., 2013; Malica et al., 2024). This also represents an interesting suggestion for future studies.

4.3. Effect of the experimental treatment on litter decomposition rate

The fifth research hypothesis (*the decomposition process in the skid trails is significantly slowed down in the short-term but returns to the pre-harvest conditions in a 10-year period*) was rejected as well. The litter decomposition rate was not accelerated nor slowed down in the skid trails in comparison to the control values and to the soil not affected by the passage of the machine (Table 4 and Fig. 4). On the one hand, the magnitude of canopy opening related to the thinning was probably too low to lead to a substantial increase in light availability able to trigger faster decomposition. On the other hand, the soil disturbance related to the passage of the machines was not enough to decrease litter decomposition rate. Although the relationship between soil disturbance after ground-based forest operations and litter decomposition rate has not been investigated much in the literature, our findings confirmed those of the few studies that dealt with this topic. Soil compaction, even when caused by heavy forest machinery, does not seem to be enough to trigger a decreased decomposition rate (Kranabetter and Chapman, 1999; Yoshida et al., 2019). Indeed, strong disturbance with soil scalping was the only treatment that caused a significant alteration of the litter decomposition rate (Enez et al., 2015). In our study areas such a level of soil disturbance was not observed, no scalping, displacement, or rutting was observed in the skid trails, even in the skid trails of the parcels harvested in 2021. From these findings, it can be suggested that the litter decomposition rate is altered primarily on heavily impacted skid trails, which are generally not established in the framework of Mediterranean beech forestry. Although our study is the first study which specifically investigates this topic, further studies will require focused and more extensive investigation. We also suggest as possible research direction to repeat the study using typical litterbags containing beech leaves and prolonging the evaluation time.

4.4. Study limitations

Although we tried to select study areas highly representative of the target context (Mediterranean beech forests) with a substantial sampling effort, we recognise that the three areas included only partly represent all the variability of Appennine beech forests, and represent the Mediterranean beech forests to an even lower degree. Future research should therefore apply our experimental design but extend the number of study areas, trying to involve more operational contexts and different soil types and textures in the research.

Furthermore, we focused on one harvesting system, which is the most used but not the only option. Other applied machinery in beech forests are forestry-fitted farm tractors equipped with forwarding bins for extracting firewood from preliminary thinnings, or forwarders which can be applied in thinnings or shelterwood cuttings. Investigation of the influence of these machines on soil features as well as on litter decomposition are welcome as a future research direction. Finally, it is worth to highlight that our surveys concerned the upper soil layer (up to a 5 cm depth), thus excluding an investigation of the disturbance which can occur to subsoil. Therefore we propose that the future research in the topic should also include an evaluation of depper soil layers.

5. Conclusion

We developed a multi-approach assessment of the soil disturbance related to ground-based forest operations in Mediterranean beech forests. In three study areas we investigated how the establishment of skid trails with medium-mechanisation level machinery affects the soil physico-chemical features (bulk density, penetration resistance, shear resistance, organic matter content), biological features (soil microarthropod biodiversity), and litter decomposition rate. We further assessed the recovery time after harvesting, to determine if a 10-year period is enough to allow for the disturbed soil to return to values in line with the soil in the unharvested control areas. We found a significant soil compaction in the first 1–2 cm of the soil (increase in penetration and shear resistance) in the skid trails in the recently harvested parcels, but no significant alteration in soil bulk density and soil organic matter. However, the values of soil microarthropod biodiversity were significantly lower in the skid trails in the recently harvested parcels in comparison to the other experimental treatments. Values of all the investigated variables in the skid trails established in the parcel harvested in 2012 showed values in line with those of the control area, suggesting that a 10-year period is enough to restore the upper soil features after thinning interventions and ground-based skidding in the studied beech forests. We further used linear mixed-effects models to investigate the relationships between soil microarthropod biodiversity and soil physico-chemical features. None of the investigated variables showed a significant relationship with soil microarthropod biodiversity, suggesting that further research efforts are needed to understand the complex interactions between ground-based forest operations and the soil edaphic fauna. Finally, we did not find a significant alteration of the litter decomposition rate in the skid trails, suggesting that light interventions and forest operations carried out with light machinery and with a limited number of machine passes on the skid trails have no negative impact on the litter decomposition process.

Our findings revealed that, despite an initial significant impact, when forest operations are carried out limiting the weight of the machine and the number of machine passes, 10 years are enough to restore the soil features in Mediterranean beech forests. Therefore scheduling further thinning or shelterwood cutting 10–15 years after the previous thinning, as occurs in the study areas, is in line with the recovery capacity of the forest soil ecosystem.

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CRediT authorship contribution statement

Francesco Latterini: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Paweł Horodecki:** Writing – review & editing, Investigation. **Marcin K. Dyderski:** Writing – review & editing, Formal analysis. **Antonio Scarfone:** Writing – review & editing, Investigation. **Rachele Venanzi:** Writing – review & editing, Investigation. **Rodolfo Picchio:** Writing – review & editing. **Andrea R. Proto:** Writing – review & editing. **Andrzej M. Jagodziński:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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