Evaluation of Leaf Litter Mulching and Incorporation on Skid Trails for the Recovery of Soil Physico-Chemical and Biological Properties of Mixed Broadleaved Forests

Meghdad Jourgholami 1, Azadeh Khoramizadeh 1, Angela Lo Monaco 2,*, Rachele Venanzi 2, Francesco Latterini 3, Farzam Tavankar 4 and Rodolfo Picchio 2

Department of Forestry and Forest Economics, Faculty of Natural Resources, University of Tehran, Karaj 999067, Iran; mjgholami@ut.ac.ir (M.J.); a.khorami.69@ut.ac.ir (A.K.)
Department of Agriculture and Forest Sciences (DAFNE), University of Tuscia, 01100 Viterbo, Italy; venanzi@unitus.it (R.V.); r.picchio@unitus.it (R.P.)
CREA Consiglio per la Ricerca in Agricoltura e l’Analisi dell’Economia Agraria-Research Centre for Engineering and Agro-Food Processing, 00015 Rome, Italy; francesco.latterini@crea.gov.it
Department of Forestry, Khalkhal Branch, Islamic Azad University, Khalkhal 56817-31367, Iran; tavankar@aukh.ac.ir
* Correspondence: lomonaco@unitus.it; Tel.: +390761357401

Abstract: Engineering applications can be used to mitigate the adverse effects of soil compaction and amend compacted soils. Previous literature has highlighted the beneficial effects of interventions such as litter mulching and incorporation on skid trails. However, little is known about the effectiveness of these alternatives in restoring forest soil quality after forest logging. The objective of this study was to properly elucidate the effects of the above mentioned soil protection methods, litter incorporation before skidding (LI) and litter mulching after skidding (LM), on the recovery of compacted soil’s physico-chemical and biological properties on skid trails over a 2-year period in the Hycranian forests of Iran to identify the best option for restoration intervention. The litter used in both methods consisted of dried leaves of the hornbeam and maple tree in three intensities of 3, 6, and 9 Mg ha$^{-1}$. The results showed that the application of both methods (LI and LM) significantly improved the soil properties when compared to the untreated skid trail. Results showed that the recovery values of soil properties in the LI treatments were significantly higher than those of the LM. The recovery values of soil properties by 6 and 9 Mg ha$^{-1}$ were significantly higher than those of 3 Mg ha$^{-1}$, while the differences were not significant between 6 and 9 Mg ha$^{-1}$. Our findings showed that soil properties were partially recovered (70–80%) over a 2-year period from treatment, compared to untreated, but the full recovery of soil properties required more time to return to the pre-harvest value. Overall, the results of this study demonstrated that the application of soil protection methods accelerates the process of recovering soil properties much faster than natural soil recovery, which can take more than 20 years in these forests.

Keywords: forest harvesting; skid trail; soil compaction; leaf litter; mulching; incorporation; soil recovery

1. Introduction

The increase in mechanized forest harvesting and the expansion of wood production areas raises questions about the environmental impact of machine traffic on forest soil and their subsequent impact on stand productivity [1–3]. Given the long-term loss of stand fertility due to the construction of skid trails, it is essential to evaluate the factors which could play a key role in achieving sustainable forest growth [4]. Scientific research has already highlighted that the passage of skidding machines can reduce the yield of forest stands as a consequence of soil compaction [5].
Forest soils play a pivotal role in maintaining the fertility, health, and services of the ecosystem [6] and provide nutrients, organic matter, and water [7]. In fact, soil compaction caused by heavy machinery in skidding operations dramatically reduces the balance and regulation of forest fertility by destroying the soil structure and disrupting the physical properties of the soil [8,9]. As a result, these phenomena led to a decrease in porosity [10], a reduction in the connection of pore spaces [11], and an increase in density and soil strength [12]. Soil compaction can further reduce water infiltration and gas exchange [13–15], with subsequent negative implications on soil macro- and micro-organisms (e.g., earthworms) [6,10], penetration and elongation of root systems [16,17], and the growth of trees and seedlings [18,19]. As documented in previous studies, such impacts are generally long lasting. Indeed, it can take several years to several decades to recover soil properties after compaction and restore it to the same pre-machine traffic conditions [2,9,10,19].

Previous studies showed that natural litter is known to be an important factor that affects soil’s physical and chemical properties [20]. Literature findings showed that litter leaves not only respond to environmental factors, but also affect many ecosystem functions [21,22] and affect soil nutrients through decomposition processes [23,24]. Thus, leaf quality largely determines litter decomposition as well as the release of nutrients and minerals into the soil layers [22], which indicates the relationship between tree leaves, the litter layer, and soil profile [25]. Therefore, application of the knowledge of leaf and litter effects on soil carbon and the organic nitrogen cycle play a key role in understanding the nutrient feeding cycle and plant-soil interactions in forest ecosystems [26].

Moreover, native broadleaf tree species alter ground surface functions that can regulate the quality of litter input and the soil-root system, which ultimately affects soil properties and nutrient content [27,28]. Therefore, the litter layer in forest ecosystems not only protects the soil surface and absorbs the effects of raindrops [29–31], but it also regulates the flow and cycle of nutrients [32].

Previous findings reported that the intrinsic characteristics of the leaves which make up forest litter, i.e., C/N ratio and lignin content, have a significant influence on the interactions between litter and soil, affecting decomposition rate, organic matter, and microbial and biological activity [21].

In addition, Jourgholami et al. [23] reported that the application of hornbeam and maple litter accelerates the recovery processes for soil organic carbon and provides more nutrients than beech litter. Therefore, litter of these species can be considered to be of high-quality.

In particular, high-quality litter accelerates biological activity (e.g., earthworms) and increases soil pH [23], which in turn modifies soil structure with different species of earthworms, resulting in increased soil aeration and improved space and bulk density of soil pores [33,34]. Further studies highlighted that native tree species such as Acer mono, Quercus mongolica, Juglans mandschurica, Fraxinus rhytchophylla, and Fraxinus mandschurica significantly maintained soil chemical and microbial properties as compared to the soil of Larix olgensis plantations over a period of 60–70 years [35]. Similarly, in a short-term laboratory study, Yang and Zhu [36] found that litter of Fraxinus mandshurica decomposed faster than other species (e.g., Quercus mongolica, Juglans mandschurica, Fraxinus rhytchophylla, and Acer mono), which ultimately led to increased microbial viability and enhanced nutrient content. Tree leaves with a higher amount of lignin, tannins, polyphenols or other recalcitrant compounds greatly inhibit the extent and rate of decomposition and determine the time required for the material to cycle through soil layers [36,37]. Accordingly, Langenbruch et al. [24] showed that the decomposition rate of ash (Fraxinus excelsior L.) was faster than that of European beech (Fagus sylvatica L.) and lime (Tilia cordata Mill.), as organic C and total N in the litter layer of beech trees were more abundant than that of ash, but organic C and total N at a depth of 0–10 cm in beech and lime were lower than ash.

Considering the negative impacts of skidding operations on forest soil, as reported above, the application of mulch can improve soil bulk density, porosity, and aggregate
stability, as well as enhance infiltration rate, increase water storage capacity, and increase the levels of organic matter content [3,38]. Mulch is any organic and inorganic materials (i.e., litter, straw, leaves, plastic film, and gravel) spread on the surface to protect the soil, as opposed to materials that are incorporated into the soil profile [39]. Jourgholami et al. [3] concluded that 1.31 kg m\(^{-2}\) of leaf litter was an optimal level for spreading on skid trails to modify and enhance soil quality. Likewise, Jourgholami et al. [23] reported that the application of sawdust mulch resulted in a partial recovery of soil bulk density, total porosity, penetration resistance, and rut depth 6 years after logging interventions. Furthermore, Fernández et al. [14] found that the application of mulch on the surface of compaction-induced soil on skid trails resulted in an improvement in soil structure.

Similarly, Jourgholami et al. [17] concluded that the recovery of soil physical and chemical properties (except for soil C/N ratio) was significantly higher three years after logging in compacted soil treated with litter and sawdust as compared to untreated soil.

Furthermore, litter incorporation into soil showed interesting features in restoring the characteristics of compacted soil after logging operations [40]. However, the application rate and incorporation depth are the main drivers for effectiveness of organic mulch to improve soil properties [41]. Surface applied plant residues decreased soil temperature and increased soil moisture content more than the incorporation of plant residues into soil [42]. However, mulching the organic materials on the soil surface increased the possible leaching of nitrate compared to the incorporation of plant residues [43]. In an urban area, Cogger et al. [44] found that the soil bulk density was significantly higher when compost was used on the surface than the incorporated compost treatment over a 6-year period after compost application.

Similarly, Kranz et al. [41] concluded that compost incorporation significantly decreased soil bulk density. Previous studies highlighted that the decomposition rates of the residues incorporated into soil are faster than the ones of surface applied organic residues [42].

Notwithstanding the attention which scientific literature has put on both the assessment of soil impacts related to forest operations and the related possible techniques of restoration, there is still a lack of knowledge regarding the effectiveness of two known restoration methodologies (litter mulching and litter incorporation before harvesting operations) when applied to logging in mixed broadleaved stands. Comparative studies between these two different approaches are indeed scarce in the current literature. Hence, the objectives of this study were to: (1) elucidate the effects of mulching and incorporation of litter on the recovery of compacted soil properties in the skid trails over a 2-year period, compared to the untreated skid trail (UNT) and undisturbed (control) area (UND), and (2) assess the efficacy of three litter application rates of 3, 6, and 9 Mg ha\(^{-1}\) on the recovery process of physico-chemical, biological, and microbial soil properties.

2. Materials and Methods

2.1. Site Description

The study area is located within compartment n. 315 in the Gorazbon district of the Kheyrud forest research station (51°37’01”–51°37’17” E, 36°33’34”–36°33’15” N) in the Hyrcanian forests of northern Iran (Figure 1a). The altitude of the study area ranges from 1150 to 1250 m asl with a southern aspect. The study area has a humid climate with a total of 1260 mm annual rainfall. The maximum and minimum monthly rainfall occurred in October and July, respectively. The mean annual temperature is 12.8 °C and the hottest and coldest months are in July and January, respectively. According to the United States Department of Agriculture (USDA) soil taxonomy, the soil type in the study area is deep brown (Alfisols), derived from limestone and dolomite limestone, belonging to the upper Jurassic and lower Cretaceous periods. The study area is dominated by natural uneven-aged stands of beech (Fagus orientalis Lipsky), with hornbeam (Carpinus betulus L.) and velvet maple (Acer velutinum Boiss). The average stem density and average growing stock of stands in the study were 227.7 tree ha\(^{-1}\) and 462.7 m\(^{3}\) ha\(^{-1}\), respectively. The average
tree dbh (diameter at breast height) and height were 48 cm and 28 m, respectively. The single tree selection system was the main silvicultural treatment in the study area. In March 2017, a total of 98 trees with 676 m$^3$ were felled and processed by chainsaw, and extracted by a wheeled skidder of TAF E655 from stump to landings in July 2017. The main technical characteristics of a TAF E655 skidder are: articulated, four-wheel-drive vehicle weighing 6.8 metric tonnes, engine power of 65 hp (48 kW), a tire size of 18.4–26 inches inflated to 659 kPa on both front and rear axles, and an overall width of 2.85 m. The slope gradient of skid trails was in the range 8–15%, the average load volume was 3.4 m$^3$, and operating trails had a width of 3.5 m.

Figure 1. The study area location in north of Iran (a) in Gorazbon District in the Hyrcanian forests (b). The LM9, skid trail with litter mulch level of 9 Mg ha$^{-1}$ (c), the UND, undisturbed (control) treatment (d), the LI9 skid trail with a litter incorporation level of 9 Mg ha$^{-1}$ (e), and the LI6, skid trail with a litter incorporation level of 6 Mg ha$^{-1}$ (f).

2.2. Experimental Design

In total, 20 pure stands of hornbeam and maple in the study area were selected and 10 sample plots of $2 \times 2$ m were installed to collect the leaf litter in each stand. The undecomposed leaf litters were collected by hand in the fall, transported to the laboratory, air-dried [45], re-weighed in each sample plot, and stored over winter before application the following year. The dried leaf litter of the hornbeam and maple were manually and evenly distributed on the skid trail segments with three application rates of 3, 6, and 9 Mg ha$^{-1}$ before and after skidding operations.
In order to compare the effects of litter mulching on the surface soil (after skidding operations) and litter incorporation into the soil (before the skidding operations) on soil properties, three segments with dimensions of $4 \times 5$ m were randomly selected on the skid trails along the slope gradient, ranging from 10 to 14%, on the skid trails exposed to the equivalent of 10 machine passes in 2017. For litter incorporation into soil before the machine entrance over the skid trails, mixed litter of hornbeam and maple (combined as a weight ratio of 1:1) were evenly scattered over the selected segments with three application amounts of $3 \times (LI3)$, $6 \times (LI6)$, and $9 \times (LI9) \text{ Mg ha}^{-1}$ for appropriate mixing of the litter with soil before the skidder traffic of 10 machine passes (Figure 1). For litter mulch treatments on soil surface, litter mulches were manually distributed on the surface soil at the determined segments with three applications in the amounts of $3 \times (LM3)$, $6 \times (LM6)$, and $9 \times (LM9) \text{ Mg ha}^{-1}$ immediately after 10 machine passes. Wire mesh was installed on the surface of the skid trail segments to capture autumn leaf fall.

In 2019, two years after incorporation on the treatment areas (LI and LM), 5 soil samples were collected in each treated segment on the mineral soil at the depth of 0–10 cm. In addition, 5 soil samples were collected in the untreated skid trails (UNT) and in the undisturbed (control) area 20 m away from the skid trails (UND). A total of 120 soil samples (i.e., 3 skid trails segments $\times 2$ type of litter applying $\times 3$ application rate $\times 5$ soil samples + 3 skid trails segments $\times 2$ references (UNT and UND) $\times 5$ soil samples) were collected and then analyzed.

### 2.3. Data Collection and Laboratory Analysis

A thin-walled steel cylinder with a length of 100 mm long and diameter of 56 mm was used to take soil sample cores from the top mineral soil (depth of 10 cm) in each sample point. Then, soil cores were weighed, stored in bags, labelled, transported to the lab, and oven-dried to constant mass at 105 °C for 24 h to measure the soil bulk density and water content [46].

Soil samples were collected from a $20 \times 20 \times 10$ cm volume, air-dried, and passed through a 2 mm sieve to measure the other soil physico-chemical properties. The soil particle size distribution was determined by the hydrometer method [47]. The water desorption method [48] was employed to determine the macroporosity. The analog hand-held soil penetrometer (Eijkelkamp 06.01.SA penetrometer with a 60° cone and a 1 m maximum measuring depth) was used to determine the soil penetration resistance (PR). The wet sieving procedure was applied [49] to determine the aggregate stability. The ASTM D854-00 2000 standard was used to determine the soil particle density, and then Equation (1) was used to calculate total porosity as follows [46]:

$$\text{TP} = 1 - \frac{M_s}{2.65 \times V_C} \times 100$$

where TP is the apparent total porosity (%), $M_s$ is mass of soil (g), $V_C$ is the volume of the intact soil cores (246.30 cm³), and 2.65 (g cm⁻³) is the particle density.

The sieved soil was analyzed to determine soil chemical properties. Soil pH was determined by the Orion Ionalyzer (Model 901) pH meter in a soil: water ratio of 1:2.5. The Walkley-Black technique was employed to determine the soil organic C [50]. To determine soil total N [51], the Kjeldahl method was used. Soil C and N storage, at a depth of 0–10 cm, was determined by Equation (2):

$$\text{SO (C or N) s} = \text{C or N} \times \text{BD} \times e \times 0.1$$

where the SO (C or N) s indicates the organic C or N storage in the soil (Mg ha⁻¹); C or N is the organic C or N content (g kg⁻¹); BD is the bulk density (g cm⁻³); $e$ is the thickness of the layers (cm), and 0.1 is a depth conversion factor.

The Olsen method, with a spectrophotometer, was employed to measure the available phosphorous (P). The available potassium (K), calcium (Ca), and magnesium (Mg) (by
ammonium acetate extraction at pH 9) were measured by using an atomic absorption spectrophotometer [52]. Manual sampling was employed at the soil surface of 25 × 25 cm with a depth of 0–10 cm to determine the number and density of earthworms [52]. The earthworms were counted in the sampling area, transported to the laboratory, washed, euthanized by placement into hot water, oven-dried at 60 °C for 24 h to reach the constant mass, and then reweighed to determine the earthworm dry mass [53]. To measure fine root biomass, fine roots (<2 mm diameter) were separated from the soil in each sample area (20 × 20 × 10 cm) and dried at 70 °C to reach a constant mass [54]. Soil microbial respiration was measured by measuring the CO₂ evolved in a 3-day incubation experiment at 25 °C [51].

2.4. Statistical Analysis

A complete block design was randomly employed to show the effects of litter (mixed hornbeam and maple) mulching on the surface soil and incorporation into the soil with three application amounts (3, 6, and 9 Mg ha⁻¹) on the skid trail to determine soil physico-chemical, biological, and microbial properties as compared to the untreated skid trail (UNT) and the undisturbed (control) treatments (UND) over a 2-year period after treating and skidding operations. The Kolmogorov–Smirnov test was used to test the normality of data distribution. The Levene test was used to test the homogeneity of variance. To compare physico-chemical, biological, and microbial properties among treatments (UND, litter mulching on surface soil (i.e., LM3, LM6, and LM9), litter incorporation into soil (i.e., LI3, LI6, and LI9), and UNT), a one-way analysis of variance (ANOVA) was employed. The Tukey’s test was applied as a post hoc for the treatment group means at \( p \leq 0.05 \), after the ANOVA detected significant differences among treatments. The Pearson correlation was employed to test the relationship between physico-chemical, biological, and microbial properties. All statistical analyses were performed using the SPSS (release 17.0; New York, NY, USA) statistical package.

3. Results

3.1. Soil Physico-Chemical Properties

The results of the ANOVA showed that both methods (litter incorporation during skidding and litter mulching after skidding) had a significant effect on all physical (Table 1), chemical (Table 2), and biological (Table 3) properties of the soil. The highest soil bulk density, penetration resistance, and amount of sand was found in the UNT, followed by LM3, LM6, and LM9, whereas the lowest soil bulk density, penetration resistance, and amount of sand was detected in the UND. Total porosity, macroporosity, and aggregate stability were significantly highest in the UND, followed by LI9 and LI6, whereas the lowest total porosity, macroporosity, and aggregate stability was measured at the UNT. The UND had the highest soil moisture, followed by LM9 and LM6, whereas the lowest soil moisture was found in the UNT. Silt under LM3 was lower as compared to other treatments, although the value was higher than the silt measured at the UNT. The highest clay content was observed on the LM9 followed by LI9, whereas the lowest clay was detected on UNT (Table 1).

The highest soil pH was found under UNT, followed by the LM3 ≈ LM6 treatments, whereas the lowest pH was observed at the UND. The highest values of soil organic C, soil C/N ratio, and C storage were detected in UND followed by LM3, whilst the lowest values of soil C, soil C/N ratio, and C storage were noted under the UNT. Significantly, the highest amount of soil N, N storage, and available nutrients (P, K, Ca, and Mg) were found under the LI9, followed by LI6, whereas these values were still less than those of the values under the UND over a 2-year period after soil compaction. Two years after applying litter mulch and incorporation, the recovery values of soil N, N storage, and available nutrients (P, K, Ca, and Mg) were significantly lower in LM3, as compared to the UNT treatment (Table 2).

Results showed that soil physico-chemical properties were partially recovered due to the application of both litter mulch on the surface of the soil and incorporation into the soil,
as compared to the UNT, although soil physical properties were still lower than the UND. Regardless of the litter mulch and incorporation application rate, the recovery of soil physico-chemical properties was higher in the incorporation treatments than the mulch treatments. For both litter mulch and incorporation, the recovery level of soil physico-chemical properties increased as the application of litter amount increased (Tables 1 and 2).

### Table 1. Mean values (±SD) of different soil physical properties in different treatments. UND, undisturbed (control); LM3, litter mulch level of 3 Mg ha\(^{-1}\); LM6, litter mulch level of 6 Mg ha\(^{-1}\); LM9, litter mulch level of 9 Mg ha\(^{-1}\); LI3, litter incorporation level of 3 Mg ha\(^{-1}\); LI6, litter incorporation level of 6 Mg ha\(^{-1}\); LI9, litter incorporation level of 9 Mg ha\(^{-1}\); and UNT, untreated treatment. Different letters after means within each treatment indicate significant differences by Tukey’s test (p < 0.05).

| Soil Properties          | Treatments | F Test | p Value |
|--------------------------|------------|--------|---------|
|                          | UND        | LM3    | LM6    | LM9    | LI3    | LI6    | LI9    | UNT    |         |
| Bulk density (g cm\(^{-3}\)) | 1.01 ± 0.24 | 1.23 ± 0.19 | 1.21 ± 0.16 | 1.12 ± 0.08 | 1.08 ± 0.13 | 1.33 ± 0.28 | 58.50  | 0.00   |
| Total porosity (%)       | 6.19 ± 2.18 | 1.99 ± 2.29 | 2.08 ± 1.92 | 1.92 ± 1.59 | 1.58 ± 1.73 | 1.72 ± 0.00 | 58.49  | 0.00   |
| Macroporosity (%)        | 44.06 ± 38.76 | 38.3 ± 38.84 | 39.67 ± 40.54 | 41.68 ± 35.24 |         |         | 23.76  | 0.00   |
| Penetration resistance (MPa) | 1.68 ± 0.96 | 1.96 ± 2.41 | 2.22 ± 2.12 | 2.16 ± 1.49 | 1.94 ± 0.90 | 0.11 ± 0.00 | 41.94  | 0.00   |
| Soil moisture (%)        | 4.12 ± 34.33 | 35.49 ± 37.43 | 31.81 ± 32.71 | 24.29 ± 29.51 |         |         | 23.09  | 0.00   |
| Aggregate stability (%)  | 50.76 ± 39.37 | 40.71 ± 43.16 | 43.28 ± 44.06 | 46.55 ± 36.76 |         |         | 45.65  | 0.00   |
| Sand (%)                 | 7.1 ± 12.6 | 11.5 ± 10.7 | 10.2 ± 8.5 | 14.5 ± 14.5 | 14.5 ± 14.5 | 14.5 ± 14.5 | 342.93 | 0.00   |
| Silt (%)                 | 54.2 ± 57.3 | 47.8 ± 44.5 | 49.7 ± 47.2 | 56.6 ± 56.6 | 56.6 ± 56.6 | 56.6 ± 56.6 | 107.54 | 0.00   |
| Clay (%)                 | 38.7 ± 34.1 | 40.7 ± 46.4 | 39.6 ± 42.6 | 45.8 ± 28.9 | 28.9 ± 28.9 | 28.9 ± 28.9 | 129.13 | 0.00   |

### Table 2. Mean values (±SD) of different soil chemical properties four years after mulching treatment. UND, undisturbed (control); LM3, litter mulch level of 3 Mg ha\(^{-1}\); LM6, litter mulch level of 6 Mg ha\(^{-1}\); LM9, litter mulch level of 9 Mg ha\(^{-1}\); LI3, litter incorporation level of 3 Mg ha\(^{-1}\); LI6, litter incorporation level of 6 Mg ha\(^{-1}\); LI9, litter incorporation level of 9 Mg ha\(^{-1}\); and UNT, untreated treatment. Different letters after means within each treatment indicate significant differences by Tukey’s test (p < 0.05).

| Soil Properties          | Treatments | F Test | p Value |
|--------------------------|------------|--------|---------|
|                          | UND        | LM3    | LM6    | LM9    | LI3    | LI6    | LI9    | UNT    |         |
| pH (1.25 H\(_2\)O)       | 5.46 ± 0.86 | 5.82 ± 5.74 | 5.77 ± 5.72 | 5.72 ± 5.77 | 5.87 ± 5.94 |          | 20.34  | 0.00   |
| C (%)                    | 9.56 ± 4.36 | 4.24 ± 3.73 | 3.33 ± 3.25 | 2.89 ± 1.16 | 1.16 ± 0.00 |          | 127.63 | 0.00   |
| N (%)                    | 1.56a ± 0.53b | 0.72b ± 0.63cd | 0.70cd ± 0.63 | 0.75d ± 0.68e |            |          | 15.63  | 0.00   |
| C/N ratio                | 23.56 ± 21.08 | 19.24 ± 14.95 | 12.6 ± 12.2 | 9.02 ± 8.75 | 13.95 ± 0.00 |           | 13.95  | 0.00   |
| C storage (Mg ha\(^{-1}\)) | 97.12 ± 54.04 | 52.08 ± 45.19 | 36.67 ± 36.54 | 31.26 ± 15.35 |          |          | 81.70  | 0.00   |
| N storage (Mg ha\(^{-1}\)) | 19.44a ± 6.81b | 8.55b ± 8.19b | 8.37cd ± 7.94cd | 8.26d ± 8.77e |          |          | 6.27   | 0.00   |
| Available P (mg kg\(^{-1}\)) | 23.25 ± 13.46 | 13.54 ± 14.63 | 15.45 ± 15.78 | 17.61 ± 11.18 | 16.57 ± 0.00 |          | 16.57  | 0.00   |
| Available K (mg kg\(^{-1}\)) | 4.62a ± 2.63cd | 2.69cd ± 3.45cd | 3.46cd ± 3.89cd | 3.77b ± 2.57d |          |          | 34.64  | 0.00   |
| Available Ca (mg kg\(^{-1}\)) | 193.56 ± 96.28 | 100.96 ± 109.62 | 121.86 ± 123.54 | 140.27 ± 78.32 |          |          | 35.74  | 0.00   |
| Available Mg (mg kg\(^{-1}\)) | 35.83a ± 15.18 | 12.87cd ± 22.55cd | 19.32bc ± 17.59bc | 30.43b ± 18.19e |          |          | 32.14  | 0.00   |
| Available (mg kg\(^{-1}\)) | 48.54 ± 24.67 | 24.46 ± 26.82 | 29.73 ± 31.43 | 34.69 ± 17.54 |          |          | 32.14  | 0.00   |
3.2. Soil Biological and Microbial Properties

Soil biological and microbial properties significantly differed ($p < 0.001$) among different litter mulching and incorporation, UND, and UNT treatments (Table 3). The greatest values of earthworm density and dry mass, fine root biomass, and soil microbial respiration were found under the UND, followed by LI9 and LI6, whereas the significantly least amount of these values was measured under the UNT treatment (Table 3).

Due to the litter mulching on the soil surface and litter incorporation into the soil, the recovery values of earthworm density and dry mass, and fine root biomass as well as soil microbial respiration, were significantly higher in the incorporation treatments (i.e., LI9, LI6, and LI3) than the litter mulching treatments (i.e., LM9, LM6, and LM3). However, the values of earthworm density and dry mass, fine root biomass, and soil microbial respiration did not return to the pre-harvest levels as observed under UND over a 2-year period, but these values were higher than the values of the UNT (Table 3).

### Table 3. Mean values (±SD) of different soil biological and microbial properties four years after mulching treatment. UND, undisturbed (control); LM3, litter mulch level of 3 Mg ha$^{-1}$; LM6, litter mulch level of 6 Mg ha$^{-1}$; LM9, litter mulch level of 9 Mg ha$^{-1}$; LI3, litter incorporation level of 3 Mg ha$^{-1}$; LI6, litter incorporation level of 6 Mg ha$^{-1}$; LI9, litter incorporation level of 9 Mg ha$^{-1}$; and UNT, untreated treatment. Different letters after means within each treatment indicate significant differences by Tukey’s test ($p < 0.05$).

| Soil Properties          | Treatments | F Test | p Value |
|--------------------------|------------|--------|---------|
| Earthworm density (n m$^{-2}$) | UND | LM3 | LM6 | LM9 | LI3 | LI6 | LI9 | UNT |        |
| 2.93 ± 1.08 ± 1.13 ± 1.25 ± 1.43 ± 1.46 ± 1.67 ± 0.68 ± | 104.14 | 0.00 |
| Earthworm dry mass (mg kg$^{-1}$) | UND | LM3 | LM6 | LM9 | LI3 | LI6 | LI9 | UNT |        |
| 43.41 ± 16.57 ± 17.14 ± 18.75 ± 21.41 ± 22.08 ± 25.37 ± 11.27 ± | 102.58 | 0.00 |
| Fine root biomass (g m$^{-2}$) | UND | LM3 | LM6 | LM9 | LI3 | LI6 | LI9 | UNT |        |
| 86.21 ± 33.64 ± 34.82 ± 36.54 ± 39.17 ± 47.54 ± 55.47 ± 27.84 ± | 51.79 | 0.00 |
| SMR | UND | LM3 | LM6 | LM9 | LI3 | LI6 | LI9 | UNT |        |
| 0.42 ± 0.18 ± 0.19 ± 0.21 ± 0.23 ± 0.24 ± 0.27 ± 0.13 ± | 26.90 | 0.00 |

Soil bulk density significantly and positively correlated with soil penetration resistance, sand, silt, and pH, and negatively correlated with total porosity, macroporosity, soil moisture, aggregate stability, clay, soil C, soil N, C and N storage, available nutrients (P, K, Ca, and Mg), earthworm density and biomass, fine root biomass, and soil microbial respiration (Table 4).

### Table 4. Pearson correlation between soil physico-chemical, biological, and microbial properties. BD = bulk density (g cm$^{-3}$), TP = total porosity (%), MP = macroporosity (%), PR = penetration resistance (MPa), SM = soil moisture (%), AS = aggregate stability (%), sand (%), silt (%), clay (%), pH = pH (1:2.5 H2O), EC = EC (ds/m), CS = C (%), NS = N (%), C/NS = C/N soil, Cseq = C storage (Mg ha$^{-1}$), Nseq = N storage (Mg ha$^{-1}$), P = P (mg kg$^{-1}$), K = K (mg kg$^{-1}$), Ca = Ca (mg kg$^{-1}$), Mg = Mg (mg kg$^{-1}$), ED = earthworm density (n m$^{-2}$), EB = earthworm biomass (mg m$^{-2}$), FRB = fine root biomass (g m$^{-2}$); and SMR = soil microbial respiration (mg CO2-C g soil$^{-1}$ day$^{-1}$). Note: * $p < 0.05$; ** $p < 0.01$.

| Soil Properties | BD | MP | PR | SM | AS | SAND | SILT | CLAY | pH | Cs | NS |
|-----------------|----|----|----|----|----|-------|------|------|----|----|----|
| TP              | -1.0 ** | -0.88 ** | 0.72 ** | -0.32 ** | -0.74 ** | 0.83 ** | 0.32 ** | -0.56 ** | 0.73 ** | -0.54 ** | -0.56 ** |
| PR              | 1 | -0.63 ** | 0.32 ** | 0.64 ** | -0.72 ** | -0.27 ** | 0.48 ** | -0.65 ** | 0.53 ** | 0.52 ** |
| SM              | 1 | -0.43 ** | -0.68 ** | 0.77 ** | 0.11 | -0.38 ** | 0.58 ** | -0.69 ** | -0.58 ** |
| AS              | 1 | 0.58 ** | -0.52 ** | 0.02 | 0.19 * | -0.41 ** | 0.64 ** | 0.34 ** |
| SAND            | 1 | -0.79 ** | -0.19 * | 0.45 ** | -0.70 ** | 0.57 ** | 0.52 ** |
| SILT            | 1 | 0.48 ** | -0.75 ** | 0.71 ** | -0.59 ** | -0.64 ** |
| CLAY            | 1 | -0.94 ** | 0.23 * | 0.18 * | -0.14 |
| pH              | 1 | -0.45 ** | 0.09 | 0.35 ** |
| Cs              | 1 | -0.49 ** | -0.47 ** |
| Cs              | 1 | 0.53 ** |
4. Discussion

4.1. Soil Physical Properties

Machinery induced soil compaction without any mitigation-restoration technique could lead to changes in the nutrient cycle by changing plant diversity, plant uptake, moisture, temperature fluctuations on the soil surface, decreased soil microbial activity, and water infiltration rate [39,55]. Soil compaction on the skid trails resulted in an alteration in the natural processes of soil biochemical parameters, which led to the loss of soluble nutrients in the downstream water. Nitrate, as an inorganic form of N, is a major nutrient in forest soils that naturally contributes to the nitrogen cycle in the environment, which is easily removed by soil leaching [56]. In line with the current study, several studies showed that disturbance and compaction of soil, and rutting following heavy machinery traffic during logging operations, drastically led to the destruction of the litter layer, which causes the soil to become a harsh environment for the forest, resulting in a reduction in the nutrient cycle [14,16].

The results of the current study revealed that the higher level recovery of soil bulk density, total porosity, and macroporosity were detected in the litter incorporation treatments (i.e., LI3, LI6, and LI9), which was more than the litter mulching treatments (i.e., LM3, LM6, and LM9), as compared to the UNT. The high recovery of soil bulk density in the litter incorporation treatments can be attributed to the faster decomposition rate of litter that was easily mixed with disturbed soil and subsequent release in soil N. For both litter mulching and incorporation, the recovery level of soil bulk density increased as the application amount of the litter increased from 3 to 9 Mg ha\(^{-1}\), as compared to the UNT.

Results of the current study revealed that the recovery level of soil penetration resistance was higher in the litter incorporation treatments than those of the litter mulching treatments, as compared to the UNT. Previous studies concluded that litter mulch application significantly accelerated the recovery of soil penetration resistance on the skid trails, which could be attributed to an increase in soil biological activities on the organic substrates and soil-root interactions [3,17,23], resulting in a restoration of soil structure and improvement of the soil’s physical properties [7,14]. By application of litter mulch at a rate of 18 Mg ha\(^{-1}\), Jourgholami et al. [23] found that the highest recovery of soil bulk density, total porosity, macroporosity, soil penetration resistance, and aggregate stability was observed in the beech-hornbeam-maple litter treatment, as compared to the untreated

| Soil Properties | CNs | Cseq | Nseq | P | K | Ca | Mg | ED | EB | FRB | SMR |
|-----------------|-----|------|------|---|---|----|----|----|----|-----|------|
| BD              | -0.19* | -0.42** | -0.33** | -0.57** | -0.63** | -0.65** | -0.69** | -0.73** | -0.73** | -0.69** | -0.65** |
| MP              | 0.24** | 0.44** | 0.03** | 0.48** | 0.58** | 0.58** | 0.62** | 0.64** | 0.65** | 0.56** | 0.56** |
| PR              | -0.27** | -0.63** | -0.43** | -0.64** | -0.67** | -0.66** | -0.68** | -0.77** | -0.76** | -0.71** | -0.68** |
| SM              | 0.39** | 0.64** | 0.27** | 0.34** | 0.58** | 0.51** | 0.43** | 0.58** | 0.57** | 0.50** | 0.38** |
| AS              | 0.19* | 0.49** | 0.35** | 0.51** | 0.74** | 0.68** | 0.66** | 0.79** | 0.79** | 0.67** | 0.58** |
| SAND            | -0.20* | -0.53** | -0.48** | -0.62** | -0.68** | -0.72** | -0.72** | -0.78** | -0.77** | -0.71** | -0.69** |
| SILT            | 0.14 | 0.18* | -0.11 | -0.04 | 0.04 | -0.03 | -0.05 | 0.04 | 0.05 | 0.06 | -0.05 |
| CLAY            | -0.02 | 0.07 | 0.27** | 0.27** | 0.23** | 0.30** | 0.32** | 0.28** | 0.27** | 0.23** | 0.31** |
| pH              | -0.17 | -0.41** | -0.31** | -0.43** | -0.62** | -0.58** | -0.59** | -0.68** | -0.68** | -0.69** | -0.43** |
| Cs              | 0.66** | 0.98** | 0.41** | 0.59** | 0.69** | 0.64** | 0.64** | 0.75** | 0.76** | 0.67** | 0.66** |
| Ns              | -0.20* | 0.48** | 0.96** | 0.67** | 0.62** | 0.63** | 0.64** | 0.67** | 0.67** | 0.67** | 0.64** |
| CsN             | 1 | 0.70** | -0.31** | 0.12 | 0.23** | 0.17 | 0.18** | 0.25** | 0.25** | 0.16 | 0.21** |
| CsNseq          | 1 | 0.59** | 0.54** | 0.64** | 0.57** | 0.58** | 0.68** | 0.68** | 0.58** | 0.59** |
| Nseq            | 1 | 0.57** | 0.49** | 0.50** | 0.50** | 0.51** | 0.52** | 0.52** | 0.52** |
| P               | 1 | 0.58** | 0.70** | 0.60** | 0.68** | 0.70** | 0.69** | 0.68** |
| K               | 1 | 0.81** | 0.70** | 0.78** | 0.79** | 0.71** | 0.63** |
| Ca              | 1 | 0.64** | 0.79** | 0.81** | 0.72** | 0.63** |
| Mg              | 1 | 0.76** | 0.78** | 0.77** | 0.65** |
| ED              | 1 | 0.98** | 0.87** | 0.72** |
| EB              | 1 | 0.86** | 0.71** |
| FRB             | 1 | 0.71** |
| SMR             | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
trails. However, these values showed significant differences with the UND treatment, even over a 5-year period.

The recovery level of soil aggregate stability was higher in the litter incorporation than the observed level in the litter mulching due to the high fine root biomass in the INC treatments. According to the results of the current study, litter incorporation treatment with a different application amount appears to restore soil physical properties more than the litter mulching treatment. Litter incorporation into soil increases the litter decomposition rate, which augments the soil moisture content and water retention, and improves the nutrients viability, leading to the restoration of the soil’s physical properties [41,42].

In addition, Jourgholami et al. [57] pointed out that the full recovery of the soil physical properties (i.e., bulk density, total porosity, and penetration resistance) did not occur with hardwood sawdust mulch (beech and hornbeam) over a 6-year period, when compared to the control, due to the high amount of 36.5 Mg ha⁻¹, which resulted in an increase in soil acidity from high lignin compounds. Furthermore, by applying four litter mulch amounts (i.e., levels of 4.2, 8.1, 13.1, and 16.9 Mg ha⁻¹), Jourgholami et al. [3] found that the highest recovery rate for soil bulk density, total porosity, macroporosity, penetration resistance, and aggregate stability were observed in the litter level of 16.9 Mg ha⁻¹ followed by a litter amount of 13.1 Mg ha⁻¹.

Results of the current study revealed that clay particles were higher in the LI9 and LM9 than in those of the treatment with a low application amount, as was also reported by Jourgholami et al. [3]. Similar results were found by Jourgholami et al. [17], since the increase in the rate of litter mulching and incorporation from 3 to 9 Mg ha⁻¹ resulted in the formation of a protective layer; this layer intercepted the raindrop erosive power and reduced clay particle detachment.

Incorporation of mulch with soil before the movement of harvesting vehicles on the surface of the skid trails led to the formation of a buffer layer between soil and machine wheels, which was able to absorb and reduce the pressure of the machine on the soil surface.

4.2. Soil Chemical, Biological and Microbial Properties

Results showed that soil pH values were higher in the litter mulching treatments than in the litter incorporation treatments. This aspect can be attributed to the high organic matter content on the surface of the soil due to the high-quality litter. High-quality litter increases the decomposition rate and enhances the cation exchange capacity, which favors soil biological activities as reported by Diao et al. [35].

Results of the current study showed that the highest recovery level for soil organic C and C/N ratio was observed in the litter incorporation treatment followed by the litter mulching treatment. According to previous studies, the highest level of soil organic C and soil C/N ratio can be attributed to the slower rate of mineralization for litter mulching treatment and the increase in soil pH in the LM3, LM6, and LM9 treatments [24,25]. The decomposition processes of carbon and nitrogen compounds following litter mulching and incorporation, as well as subsequent mixing with mineral particles, led to improvement in soil C and N. Soil organic C mainly contributed to enhance the structure of soil and sustained the food substrates, which led to an increase in microbial and biological activities.

This study showed that the recovery values for N and N storage were significantly higher in the litter incorporation treatments (i.e., LI9, LI6, and LI3) than the litter mulching treatments (i.e., LM9, LM6, and LM3), as compared to the UNT. The high-quality litter of hornbeam-maple, which was incorporated into the soil, resulted in an increase in the decomposition rate, improved soil pH, and, ultimately, accelerated N release. Results showed that the application of the high-quality litter of tree species, including hornbeam and maple litters, as mulch on the soil surface or incorporation into the soil increased the N delivery into soil layers, which ultimately regulated nutrient cycling [17]. Moreover, litter mulch C/N ratio was an important factor that regulated the decomposition rate and subsequent nutrient release into the soil layers [21]. Instead, applying litter with recalcitrant compounds regulated the nitrogen, lignin, and the C/N and lignin/nitrogen
ratios in litter [58], which not only increased soil C/N ratio, but also led to the accumulation of the organic matter content on the soil surface [36,58].

The results showed that litter mulching on the soil surface was a determining factor in the improvement of the C storage (3.7–4.36 Mg ha$^{-1}$), more so than the litter incorporation treatments (2.89–3.33 Mg ha$^{-1}$). Hence, application of litter mulch and incorporation in the compacted soil can significantly increase the carbon sequestration, which plays a key role in accelerating the restoration of disturbed soil after heavy machinery traffic.

The results of the present study elucidated that the highest recovery level of available nutrients (P, K, Mg, and Ca) was observed in the litter incorporation treatments, including LI9, LI6, and LI3, followed by LM9, LM6, and LM3, when compared to the UNT. However, these values, for both litter incorporation and mulching, were still lower than the value of the undisturbed treatment (UND). Failing leaves on the surface of the soil, especially high-quality litter, appeared to have a crucial role in regulating the food resources, including organic matter content and soil C, and as an important key factor for microbial activities [59]. In accordance with the results of the current study, previous studies showed that alteration in litter and topsoil properties, highly related to native and non-native tree species, were mainly attributed to the quality of litter [26,35]. After application of litter mulch ranging from 4.2–16.9 Mg ha$^{-1}$, Jourgholami et al. [3] determined that soil N, N sequestration, and available nutrients (i.e., P, K, Ca, and Mg) were at the highest level in litter mulch applied in the amount of 16.9 Mg ha$^{-1}$, and at the lowest level in litter treatment in the amount of 4.2 Mg ha$^{-1}$.

The highest recovery level of available soil nutrients (i.e., P, K, Ca, and Mg) in litter incorporation into the soil can be attributed to the labile components of hornbeam-maple litter, the low content of lignin, and the high content of N leading to the greater lignin/nitrogen ratio, which decomposed faster than the litter mulching on the soil surface. Similar observations were made by Maggard et al. [60], Aponte et al. [22], Langenbruch et al. [24], and Diao et al. [35]. In the current study, the recovery values of the earthworm density and dry mass were higher in the litter incorporation treatments (i.e., LI9, LI6, and LI3) than those of the litter mulch treatments (i.e., LM9, LM6, and LM3) which can be attributed to the lower C and C/N ratio, higher N, and available nutrients [3]. However, Bottinelli et al. [10] reported that the recovery of earthworm density and biomass did not occur over a 4-year period due to the harsh environment in the compaction-induced soil after logging operations. Both litter mulching on the soil surface and incorporation into the soil led to the stimulation of soil micro-organisms (i.e., algae, mosses, fungi, and bacteria) and macro-organisms like earthworms [61]. Induced compaction is thought to degrade the soil quality and may accelerate the formation of a hostile environment for populations of soil organisms, with an undesirable impact on ecosystem engineers such as earthworms [10]. Instead, adding litter mulch enhances the food substrates, which encourage earthworm movement into the soil, leading to the enhancement of soil structure and the nutrient cycle [61].

Apart from the effects of organic mulches on improving soil quality conditions, another important aspect is their role in soil and water conservation. Previous studies have revealed that skid trails were considered an important non-point source to produce runoff and soil erosion [3,26,29,30,62]. Mulch application can protect the surface of bare mineral soil and play a crucial role in soil and water conservation [38]. Previous studies indicated that application of mulch increased the soil cover, absorbed the raindrops hitting the soil surface, and enhanced the ground roughness of the soil surface, which resulted in an increase of water infiltration into the soil layer, reduced surface runoff, decreased soil detachment, and reduced sediment and nutrient losses [17,23,26,57]. Mulch application can led to altered hydrological connectivity at the headwater catchment [62]. In the current study, splash erosion was the main erosion process, rather than other erosion processes such as rill and interrill, due to the shorter length of plot as reported by Bagarello and Ferro [63]. In the Hyrcanian forests, Jourgholami et al. [26] concluded that the application of leaf litter with rate of 4.2–16.9 Mg ha$^{-1}$ resulted in a decrease in runoff from 49% to 79% and sediment
yield from 76% to 93%. By reviewing the studies in agricultural areas, Li [38] concluded that a mulch application rate of 6–8 Mg ha\(^{-1}\) can be effective at mitigating runoff and soil loss. However, López-Vicente et al. [62] demonstrated that check-dam installation in the skid trails areas can play an important role in suppressing sediment delivery into water bodies.

Results of this study demonstrated that the recovery levels of fine root biomass were higher in the litter incorporation treatments than in those of the litter mulching treatments, as compared to the UNT. Similar to our findings, Jourgholami et al. [39] reported that increasing the application amount of litter resulted in an increase of the recovery values of fine root biomass. Likewise, Jourgholami et al. [23] concluded that litter mulching on the soil surface led to a restoration of the values of fine root biomass. The results showed that induced compaction significantly reduced the amount of organic matter and depth of litter layer, which negatively affected the soil microbial biomass. The findings of this study revealed that the recovery values of soil microbial respiration were higher in the litter incorporation into soil treatment than in the litter mulching on the soil surface. The faster recovery values observed in the litter incorporation treatments can be related to the high-quality litter, with lower levels of carbon and lignin, which resulted in a faster decomposition rate and higher nutrient release.

The period of 1–2 years after machinery traffic on the skid trail is a very crucial period in which to apply best management practices (BMPs), such as mulching, to mitigate surface runoff and soil erosion. However, organic mulches, such as leaf litter, were decomposed one or two years after the fall. Hence, the effect of organic mulch on soil quality can appear one to two years after mulching, although the long-term effects of soil compaction may take a few years to several decades to dissipate.

5. Conclusions

In the present study, the effects of litter (a mixture of hornbeam and maple) mulching on the surface soil and incorporation into the soil, with three application amounts (3, 6, and 9 Mg ha\(^{-1}\)), on the skid trails to restore the soil physico-chemical, biological, and microbial properties were tested, and compared to the untreated skid trail (UNT) and the undisturbed (control) treatments (UND) over a 2-year period after treating and skidding operations. Our findings demonstrated that the recovery values of physico-chemical, biological, and microbial soil properties were significantly higher in the litter incorporation treatments (i.e., LI9, LI6, and LI3) than those of the litter mulching treatments on the soil surface (i.e., LM9, LM6, and LM3). Results of the current study elucidated that physico-chemical, biological, and microbial soil properties were partially recovered over a 2-year period from treatments, as compared to the untreated skid trail (UNT), but the full recovery of soil properties required more time before it returned to the pre-harvest value or values of the undisturbed treatments (UND). Regardless of litter mulching or incorporation, as litter amount increased from 3 to 9 Mg ha\(^{-1}\), the recovery level for physico-chemical, biological, and microbial soil properties increased compared to the UNT, but these values were still different from the values of the undisturbed treatments (UND) even 2-years after soil compaction and litter applications. According to the current results, litter incorporation into the soil was more effective for soil restoration than litter mulching. Some BMPs that can be applied to mitigate the adverse impacts and regulate soil and water conservation are:

- Application of the harvesting residues and organic mulch before the forestry vehicle traffic or incorporation instead of mulching after harvesting operations;
- Litter incorporation into the soil with the application of an amount ranging between 6–9 Mg ha\(^{-1}\) as an effective method to restore the compaction-induced soil to the same conditions before the logging operations on the skid trails;
- Mulching and incorporation of organic materials on the skid trails to mitigate surface runoff and rill and interrill erosion.
Author Contributions: Conceptualization, M.J., A.K., F.T. and R.P.; data curation, M.J., A.K., R.V., F.L., F.T. and R.P.; formal analysis, M.J., A.K., A.L.M., R.V., F.L., F.T. and R.P.; funding acquisition, A.L.M. and R.P.; investigation, M.J., A.K. and F.T.; methodology, M.J., A.K., A.L.M., R.V., F.L., F.T. and R.P.; resources, M.J., A.K., A.L.M., F.T. and R.P.; supervision, M.J.; validation, M.J., A.K., A.L.M., R.V., F.L., F.T. and R.P.; visualization, M.J., A.K., A.L.M., R.V., F.L., F.T. and R.P.; writing—original draft, M.J., A.K., F.L., F.T. and R.P.; writing—review and editing, A.L.M., R.V. and R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was, in part, carried out within the framework of the MIUR (Italian Ministry for Education, University and Research) initiative “Departments of Excellence” (Law 232/2016), WP3&4, which financed the Department of Agriculture and Forest Science at the University of Tuscia. Authors would like to acknowledge the editor and the anonymous reviewers who provided useful comments and constructive suggestions which improved a previous version of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Picchio, R.; Mederski, P.S.; Tavankar, F. How and How Much, Do harvesting activities affect forest soil, regeneration and stands? Curr. For. Rep. 2020, 6, 115–128. [CrossRef]

2. Picchio, R.; Latterini, F.; Mederski, P.S.; Venanzi, R.; Karaszewski, Z.; Bembenek, M.; Croce, M. Comparing accuracy of three methods based on the GIS environment for determining winching areas. Electronics 2019, 8, 53. [CrossRef]

3. Jourgholami, M.; Feghhi, J.; Picchio, R.; Tavankar, F.; Venanzi, R. Efficiency of leaf litter mulch in the restoration of soil physiochemical properties and enzyme activities in temporary skid roads in mixed high forests. Catena 2021, 198, 105012. [CrossRef]

4. DeArmond, D.; Ferraz, J.; Higuchi, N. Natural Recovery of Skid Trails. A Review. Can. J. For. Res. 2021. [CrossRef]

5. Sohrabi, H.; Jourgholami, M.; Jafari, M.; Shabanian, N.; Venanzi, R.; Tavankar, F.; Picchio, R. Soil recovery assessment after timber harvesting based on the sustainable forest operation (SFO) perspective in iranian temperate forests. Sustainability 2020, 12, 2874. [CrossRef]

6. Sohrabi, H.; Jourgholami, M.; Jafari, M.; Tavankar, F.; Venanzi, R.; Picchio, R. Earthworms as an ecological indicator of soil recovery after mechanized logging operations in mixed beech forests. Forests 2021, 12, 18. [CrossRef]

7. Meyer, C.; Lüscher, P.; Schulin, R. Enhancing the regeneration of compacted forest soils by planting black alder in skid lane tracks. Eur. J. For. Res. 2014, 133, 435–465. [CrossRef]

8. Picchio, R.; Pignatti, G.; Marchi, E.; Latterini, F.; Benanchi, M.; Foderi, C.; Venanzi, R.; Verani, S. The application of two approaches using GIS technology implementation in forest road network planning in an Italian mountain setting. Forests 2018, 9, 277. [CrossRef]

9. Mohieddinne, H.; Brasseur, B.; Spichler, F.; Gallet-Moron, E.; Buridant, J.; Kobaissi, A.; Horen, H. Physical recovery of forest soil after compaction by heavy machines, revealed by penetration resistance over multiple decades. For. Ecol. Manag. 2019, 449, 117472. [CrossRef]

10. Bottinelli, N.; Hallaire, V.; Goutal, N.; Bonnaud, P.; Ranger, J. Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effect and short-term recovery. Geoderma 2014, 217, 10–17. [CrossRef]

11. Sohrabi, H.; Jourgholami, M.; Tavankar, F.; Venanzi, R.; Picchio, R. Post-harvest evaluation of soil physical properties and natural regeneration growth in steep-slope terrains. Forests 2019, 10, 1034. [CrossRef]

12. Picchio, R.; Mercurio, R.; Venanzi, R.; Gratani, L.; Giallonardo, T.; Lo Monaco, A.; Frattaroli, A.R. Strip clear-cutting application and logging typologies for renaturalization of pine afforestation—A case study. Forests 2018, 9, 566. [CrossRef]

13. Goutal, N.; Boivin, P.; Ranger, J. Assessment of the natural recovery rate of soil specific volume following forest soil compaction. Soil Sci. Soc. Am. J. 2012, 76, 1426–1433. [CrossRef]

14. Fernández, J.L.F.; Hartmann, P.; Schäffer, J.; Puhlmann, H.; von Wilpert, K. Initial recovery of compacted soil—planting and technical treatments decrease CO2 concentrations in soil and promote root growth. Ann. For. Sci. 2017, 74, 73. [CrossRef]

15. Hansson, L.; Simunek, J.; Ring, E.; Bishop, K.; Gårdenäs, A.I. Soil compaction effects on root-zone hydrology and vegetation in boreal forest clearcuts. Soil Sci. Soc. Am. J. 2019, 83, S105–S115. [CrossRef]

16. Jourgholami, M.; Khoramizadeh, A.; Zenner, E.K. Effects of soil compaction on seedling morphology, growth, and architecture of chestnut-leaved oak (Quercus castaneifolia). iFor.-Biogeosci. For. 2016, 10, 145. [CrossRef]
17. Jourgholami, M.; Fathi, K.; Labelle, E.R. Effects of litter and straw mulch amendments on compacted soil properties and Caucasian alder (Alnus subcordata) growth. New For. 2020, 51, 349–365. [CrossRef]

18. Labelle, E.R.; Kammermeier, M. Above- and belowground growth response of Pinus nigra seedlings exposed to varying levels of soil relative bulk density. Eur. J. For. Res. 2019, 138, 705–722. [CrossRef]

19. Tavankar, F.; Picchio, R.; Nikooy, M.; Jourgholami, M.; Naghdi, R.; Latterini, F.; Venanzi, R. Soil natural recovery process and Fagus orientalis lipsky seedling growth after timber extraction by wheeled skidder. Land 2021, 10, 113. [CrossRef]

20. Oliveira, I.R.; Bordron, B.; Laclau, J.-P.; Paula, R.R.; Ferraz, A.V.; Gonçalves, J.L.M.; Le Maire, G.; Bouillet, J.-P. Nutrient deficiency enhances the rate of short-term belowground transfer of nitrogen from Acacia mangium to Eucalyptus trees in mixed-species plantations. For. Ecol. Manag. 2021, 491, 119192. [CrossRef]

21. Hagen-Thorn, A.; Callesen, I.; Armolaitis, K.; Nihlgård, B. The impact of six European tree species on the chemistry of mineral topsoil in forest plantations on former agricultural land. For. Ecol. Manag. 2004, 195, 373–384. [CrossRef]

22. Aponte, C.; García, L.V.; Marañón, T. Tree species effects on nutrient cycling and soil biota: A feedback mechanism favouring species coexistence. For. Ecol. Manag. 2013, 309, 36–46. [CrossRef]

23. Jourgholami, M.; Nasirian, A.; Labelle, E.R. Ecological restoration of compacted soil following the application of different leaf litter mulches on the skid trail over a five-year period. Sustainability 2018, 10, 2148. [CrossRef]

24. Langenbruch, C.; Helfrich, M.; Wagenbrenner, J.W. Effects of the successive planting of Eucalyptus urophylla on soil bacterial and fungal community structure, diversity, microbial biomass, and enzyme activity. Land Degrad. Dev. 2019, 30, 636–646. [CrossRef]

25. Langenbruch, C.; Helfrich, M.; Wagenbrenner, J.W. Effects of the successive planting of Eucalyptus urophylla on soil bacterial and fungal community structure, diversity, microbial biomass, and enzyme activity. Land Degrad. Dev. 2019, 30, 636–646. [CrossRef]

26. Jourgholami, M.; Labelle, E.R.; Feghhi, J. Efficacy of leaf litter mulch to mitigate runoff and sediment yield following mechanized operations in the Hyrcanian forests. J. Soils Sediments 2019, 19, 2076–2088. [CrossRef]

27. Zhu, L.; Wang, X.; Chen, F.; Li, C.; Wu, L. Effects of the successive planting of Eucalyptus urophylla on soil microbial and fungal community structure, diversity, microbial biomass, and enzyme activity. Land Degrad. Dev. 2019, 30, 636–646. [CrossRef]

28. Mayer, M.; Prescott, C.E.; Abaker, W.E.A.; Augusto, L.; Cécillon, L.; Ferreira, G.W.D.; James, J.; Jandl, R.; Katzensteiner, K.; Laclau, J.P.; et al. Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For. Ecol. Manag. 2020, 466, 118127. [CrossRef] [PubMed]

29. Ababi, M.E.; Majnounian, B.; Malekian, A.; Jourgholami, M. Effects of forest harvesting on runoff and sediment characteristics in the Hyrcanian forests, northern Iran. Eur. J. For. Res. 2017, 136, 375–386. [CrossRef]

30. Jourgholami, M.; Labelle, E.R. Effects of plot length and soil texture on runoff and sediment yield occurring on machine-trafficked soils in a mixed deciduous forest. Ann. For. Sci. 2020, 77, 1–11. [CrossRef]

31. Prats, S.A.; Malvar, M.C.; Wagenbrenner, J.W. Compaction and cover effects on runoff and erosion in post-fire salvage logged areas in the Valley Fire, California. Hydrol. Process. 2021, 35, e13997. [CrossRef]

32. Sayer, E.J. Using experimental manipulation to assess the roles of leaf litter in the functioning of forest ecosystems. Biol. Rev. 2006, 81, 1–31. [CrossRef] [PubMed]

33. Marty, C.; Houle, D.; Gagnon, C.; Courchesne, F. The relationships of soil total nitrogen concentrations, pools and C:N ratios with climate, vegetation types and nitrogen deposition in temperate and boreal forests of eastern Canada. Catena 2017, 152, 163–172. [CrossRef]

34. Ampoorter, E.; De Schrijver, A.; De Frenne, P.; Hermy, M.; Verheyen, K. Experimental assessment of ecological restoration options for compacted forest soils. Ecol. Lett. 2013, 17, 1374–1376. [CrossRef]

35. Diao, M.; Yang, K.; Zhu, J.; Li, M.; Xu, S. Native broad-leaved tree species play key roles on maintaining soil chemical and microbial properties in a temperate secondary forest, Northeast China. For. Ecol. Manag. 2020, 462, 117971. [CrossRef]

36. Yang, K.; Zhu, J.-J. Impact of tree litter decomposition on soil biochemical properties obtained from a temperate secondary forest in Northeast China. J. Soils Sediments 2015, 15, 13–23. [CrossRef]

37. Vauramo, S.; Setälä, H. Decomposition of labile and recalcitrant litter types under different plant communities in urban soils. Urban Ecosyst. 2011, 14, 59–70. [CrossRef]

38. Li, R.; Li, Q.; Pan, L. Review of organic mulching effects on soil and water loss. Arch. Agron. Soil Sci. 2021, 67, 136–151. [CrossRef]

39. Jourgholami, M.; Karami, S.; Tavankar, F.; Lo Monaco, A.; Picchio, R. Effects of slope gradient on runoff and sediment yield on machine-induced compacted soil in temperate forests. Forests 2021, 12, 49. [CrossRef]

40. Jourgholami, M.; Khajavi, S.; Labelle, E.R. Recovery of forest soil chemical properties following soil rehabilitation treatments: An assessment six years after machine impact. Croat. J. For. Eng. 2020, 41, 163–175. [CrossRef]

41. Kranz, C.N.; McLaughlin, R.A.; Johnson, A.; Miller, G.; Heitman, J.L. The effects of compost incorporation on soil physical properties in urban soils–A concise review. J. Environ. Manag. 2020, 261, 110209. [CrossRef]

42. Chen, B.; Liu, E.; Tian, Q.; Yan, C.; Zhang, Y. Soil nitrogen dynamics and crop residues. A review. Agron. Sustain. Dev. 2014, 34, 429–442. [CrossRef]

43. Coppens, F.; Garnier, P.; Findeling, A.; Merckx, R.; Recous, S. Decomposition of mulched versus incorporated crop residues: Modelling with PASTIS clarifies interactions between residue quality and location. Soil Biol. Biochem. 2007, 39, 2339–2350. [CrossRef]
44. Cogger, C.; Hummel, R.; Hart, J.; Bary, A. Soil and redosier dogwood response to incorporated and surface-applied compost. *HortScience* 2008, 43, 2143–2150. [CrossRef]
45. Zagyvai-Kiss, K.A.; Kalicz, P.; Szilágyi, J.; Gribovszki, Z. On the specific water holding capacity of litter for three forest ecosystems in the eastern foothills of the Alps. *Agric. For. Meteorol.* 2019, 278, 107656. [CrossRef]
46. Mulumba, L.N.; Lal, R. Mulching effects on selected soil physical properties. *Soil Tillage Res.* 2008, 98, 106–111. [CrossRef]
47. Gee, G.W.; Bauder, J.W. Particle-size analysis. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; Soil Science Society of America: Madison, WI, USA, 1986; pp. 383–411.
48. Danielson, R.E.; Southerland, P.L. Porosity. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; Soil Science Society of America: Madison, WI, USA, 1986; pp. 443–460.
49. Kemper, W.D.; Rosenau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; Soil Science Society of America: Madison, WI, USA, 1986; pp. 425–442.
50. Walkley, A.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 1934, 37, 29–38. [CrossRef]
51. Kooch, Y.; Zaccone, C.; Lamersdorf, N.P.; Tonon, G. Pit and mound influence on soil features in an Oriental Beech (*Fagus orientalis* Lipsky) forest. *Eur. J. For. Res.* 2014, 133, 347–354. [CrossRef]
52. Salehi, A.; Ghorbanzadeh, N.; Kahneh, E. Earthworm biomass and abundance, soil chemical and physical properties under different poplar plantations in the north of Iran. *J. For. Sci.* 2013, 59, 223–229. [CrossRef]
53. Kooch, Y.; Tavakoli, M.; Akbarinia, M. Tree species could have substantial consequences on topsoil fauna: A feedback of land degradation/restoration. *Eur. J. For. Res.* 2018, 137, 793–805. [CrossRef]
54. Neatrour, M.A.; Jones, R.H.; Golladay, S.W. Correlations between soil nutrient availability and fine-root biomass at two spatial scales in forested wetlands with contrasting hydrological regimes. *Can. J. For. Res.* 2005, 35, 2934–2941. [CrossRef]
55. Shah, N.W.; Nisbet, T.R. The effects of forest clearance for peatland restoration on water quality. *Sci. Total Environ.* 2019, 693, 133617. [CrossRef] [PubMed]
56. Kaila, A.; Sarkkola, S.; Laurén, A.; Ukonmaanaho, L.; Koivusalo, H.; Xiao, L.; O’Driscol, C.; Tervahauta, A.; Nieminen, M. Phosphorus export from drained Scots pine mires after clear-felling and bioenergy harvesting. *For. Ecol. Manag.* 2014, 325, 99–107. [CrossRef]
57. Jourgholami, M.; Khajavi, S.; Labelle, E.R. Mulching and water diversion structures on skid trails: Response of soil physical properties six years after harvesting. *Ecol. Eng.* 2018, 123, 1–9. [CrossRef]
58. Krishna, M.P.; Mohan, M. Litter decomposition in forest ecosystems: A review. *Energy Ecol. Environ.* 2017, 2, 236–249. [CrossRef]
59. Althoff, P.S.; Todd, T.C.; Thien, S.J.; Callaham Jr, M.A. Response of soil microbial and invertebrate communities to tracked vehicle disturbance in tallgrass prairie. *Appl. Soil Ecol.* 2009, 43, 122–130. [CrossRef]
60. Maggard, A.O.; Will, R.E.; Hennessey, T.C.; McKinley, C.R.; Cole, J.C. Tree-based mulches influence soil properties and plant growth. *Horttechnology* 2012, 22, 353–361.
61. Kader, M.A.; Senge, M.; Mojid, M.A.; Ito, K. Recent advances in mulching materials and methods for modifying soil environment. *Soil Tillage Res.* 2017, 168, 155–166. [CrossRef]
62. Lopez-Vicente, M.; Sun, X.; Onda, Y.; Kato, H.; Gomi, T.; Hiraoka, M. Effect of tree thinning and skidding trails on hydrological connectivity in two Japanese forest catchments. *Geomorphology* 2017, 292, 104–114.63. [CrossRef]
63. Bagarello, V.; Ferro, V. Analysis of soil loss data from plots of differing length for the Sparacia experimental area, Sicily, Italy. *Biosyst. Eng.* 2010, 105, 411–422. [CrossRef]