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Restoring soil properties in the Hyrcanian forests from machine induced compaction: Reforestation of N_2-fixing black alder (*Alnus glutinosa* (L.) Gaertn.)

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Abstract

Among the various species of trees, black alder (*Alnus glutinosa* (L.) Gaertn.) is one of the most commonly used trees for the reforestation and restoration programs of degraded forestlands in the Hyrcanian forest, particularly in the skid trails. The effects of reforestation with black alder on the recovery of litter (thickness, C, N, C/N) and soil physicochemical, biochemical, biological, and microbial properties in the skid trails with three levels of compactions were examined over a 27-year period. Results showed that the litter characteristics such as thickness, carbon (C), nitrogen (N), and C/N were at the highest level in low intensity traffic as compared to those of medium and frequent intensities. Results showed that the values of total porosity, macroporosity, aggregate stability, silt, and clay were at the lowest level in the natural stand. The highest values of soil pH, C, C/N ratio, and C storage were recorded under the skid trail with frequent machine passages. The restoration values of soil physical and chemical properties were significantly higher in the low level of machine traffic after a period of 27 years where black alder reforestation was performed on the skid trails, as compared to the medium and frequent machine traffic levels, as well as the undisturbed area. Black alder litter affected soil nitrogen and the maximum amounts of earthworm density and dry mass. This also includes fine root biomass. These data were recorded in the trails with low machine traffic as compared to those of medium and frequent traffic. The results clearly showed that black alder is effective in reaching the objectives of restoration programs, given that it promotes soil organic matter, builds up soil structure via root-soil feedback, and improves the soil by creating a major source of nitrogen through enhancing the nitrogen cycle.

KEYWORDS

biochemical and biological properties, *Carpinus betulus*, microbial properties, *Parrotia persica*, skid trail, soil compaction, soil recovery

1 | INTRODUCTION

Soils are vital components of forest ecosystems that warrant forest fertility and biodiversity preservation by controlling water and nutrient cycles (Labelle et al., 2022; Nazari et al., 2023; Picchio et al., 2021). For example, forest soils reserve >40% of the total organic carbon (C) in terrestrial ecosystems and are thus important regulators of CO_2 on a global scale (Jourgholami, Fathi, &

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Labelle, 2020; Jourgholami, Khajavi, & Labelle, 2020; Wei et al., 2014). Timber harvesting normally causes a decrease in soil carbon stocks (DeArmond et al., 2021; Latterini et al., 2023; Mayer et al., 2020). In addition, mechanized harvesting and logs transported by ground-based skidding machines can disturb forest soils and decrease periodically the productivity of the forest (Horn et al., 2004; Labelle et al., 2022; Venanzi et al., 2019). Although the capacity and power of forest harvesting machines have been enhanced in recent decades, they have also become weighty (Horn et al., 2004; Jourgholami, Khajavi, & Labelle, 2018; Jourgholami, Nasirian, & Labelle, 2018; Vossbrink & Horn, 2004). This causes disturbance on forest soils and consequently the impact of the logging operations on the forest ecosystem can be prolonged over time (Grünberg et al., 2023; Nazari et al., 2020; Picchio et al., 2020).

Soil compaction is one of the most evident types of impact caused by mechanized wood harvesting operations, which is caused by dynamic forces to the soil (Karami et al., 2023; Nazari et al., 2021). Soil disturbances and rut formations resulting from the traffic of forestry machines in the logging trails consist of alterations of the properties of forest soil and thus change the health status of the forest ecosystems (Nazari et al., 2023; Powers et al., 2004; Tavankar et al., 2018). The forest soils have low bulk density due to the high level of organic content (Corti et al., 2002), which is susceptible to compaction (Nazari et al., 2021; Powers et al., 2004). The total porosity of the soil decreases in the range of 50%–60% following the increase in bulk density imposed by compaction (Frey et al., 2009; Picchio et al., 2012).This leads to the disruption of oxygen distribution and soil water equilibrium in soil, inducing overland flow, and soil loss (Ampoorter et al., 2007; Grace et al., 2006). As a result, the access of tree roots and soil micro- and macro-organisms to oxygen and water is diminished, which leads to an overall decrease in forest fertility (Jourgholami, Ghassemi, & Labelle, 2019; Jourgholami & Labelle, 2020; Jourgholami, Labelle, & Feghhi, 2019; Kozlowski, 1999; Nazari et al., 2021).

Logging operations cause different types of corruption to the soil such as soil compaction and disturbance. Such impacts can cause alterations in biogeochemical cycles (Sohrabi et al., 2019) and hydrological disturbance (Picchio et al., 2021; Sohrabi et al., 2022). Alterations in soil conditions influence soil properties to some extent (Sohrabi et al., 2021; Zetterberg et al., 2013). Soil compaction causes changes and has effects on gaseous exchange, temperature, and the effect of water cycles on soil organisms and plants. These factors lead to negative consequences on soil ecological conditions and future forest productivity (Jourgholami et al., 2021; McNabb et al., 2001; Picchio et al., 2019, 2020). For example, one of the common causes of weak plant growth is the reduction of nutrients available to the plant (Bottinelli et al., 2014; Frey et al., 2009; Sohrabi et al., 2020). The increase in soil bulk density reduces pore size, water permeability, and gas exchange rate, which, in turn, negatively affect the propagation of the root system and plant growth (Cambi et al., 2017; Han et al., 2006). An increase in the soil moisture content means reducing the friction forces between soil particles, which reduces the soil bearing capacity (Han et al., 2006; McNabb et al., 2001). Studies have shown that the limitation of the availability of nutrients and water affects the rate of seed germination, root mass and length, and plant height (Cambi et al., 2017; Mariotti et al., 2020).

Studies conducted by different authors (Goutal et al., 2012; Mohieddinnea et al., 2019) show that the period of time elapsed since harvesting operations is very important for the analysis of the soil cover restoration processes. Restoration processes continue for a few decades from logging operations, and in some cases the damage is irreversible (Goutal et al., 2012; Klaes et al., 2016). Given that there are many factors, the process of restoration of the soil properties will vary (Bowd et al., 2019; Picchio et al., 2020). Recovery processes depend on the degree of initial compaction, which means that the type of harvesting machine selected, and the applied technology can regulate the processes of recovery (Picchio et al., 2018). Furthermore, if periods longer than 30 years are required for the recovery of soil in the skid trails, the area covered by skid trails should be considered as infertile for stand regrowth, unless tillage is applied (DeArmond et al., 2019).

Soil reclamation is naturally regulated by contrasting weather conditions, such as wet-dry and freeze-thaw processes (Sveistrup et al., 2005). Previous studies demonstrated that vegetation is acknowledged to be a crucial element that influences the soil physical and chemical properties (Diao et al., 2020; Oliveira et al., 2021). Numerous studies have observed that the forest floor not only reacts to ecological factors, but also influences many ecosystem capacities (Aponte et al., 2013; Hagen-Thorn et al., 2004) and the nutrient pool throughout the process of decomposition (Langenbruch et al., 2012). Therefore, litter quality largely regulates litter decomposition and the release of nutrient and mineral materials in soil layers (Aponte et al., 2013), which determines the relationship among tree leaves, litter, and soil characteristics (Lucas-Borja et al., 2019). Thus, the effect of litter and the organic layer on soil organic nitrogen and carbon cycle plays an indispensable function to determine the nutrient pool and plant-soil synergies in the forest ecosystem.

Native broadleaf trees amend the soil litter layer by the quality of leaves input and the root-soil system, which eventually influences soil characteristics and nutrient pool (Diao et al., 2020; Mayer et al., 2020). The floor layer in forest stands not only covers the soil surface and mitigates the hits of raindrops (Jourgholami & Labelle, 2020; Prats et al., 2021), but also governs the flow and cycling of nutrients (Sayer, 2006). Different qualities of litter mainly nitrogen, soil C, and lignin regulate the C/N ratio, which affects organic matter decomposition, microbial and biological activities (Hagen-Thorn et al., 2004; Sayer, 2006).

Research has been done on the topic of the restoration of soil properties in various regions of the world. For example, von Wilpert and Schäffer (2006) used the gas diffusion coefficient and fine root distribution to describe soil performance disturbances, which were still detectable after several decades, and reported that the traffic of heavy machinery decreased the intensity of gas permeability in the soil and consequently reduced the root penetration, observing that the soil did not recover until 14 years after the event of machine traffic. Also, Miletić et al. (2012) found that most of the dead organic

residues that reach the soil under black alder (*Alnus glutinosa* (L.) Gaertn.) are subject to rapid decomposition into final products, leading to a narrow C/N ratio in alder litter. Accordingly, Bottinelli et al. (2013) concluded that heavy traffic has an unfavorable effect on earthworm density and biomass, but the earthworm population had fully recovered 4 years after compaction. Alder planting has a high potential as an environmental action to hasten the structural reconstruction of forest soils after compaction in humid temperate regions (Meyer et al., 2014). Furthermore, Meyer et al. (2014) evaluated the potential of expediting soil amendment by planting black alder (*Alnus glutinosa* (L.) Gaertn.) in skid trails and found that tree increment was very vigorous in the skid trails after a period of 6 years. However, no information about the restoration of soil properties according to the various degrees of compaction was reported.

So far, long-term studies have been conducted on the reclamation of the soil physical and chemical characteristics along the skid trails, but there has been no long-term study on the effect of planting the same species on the restoration of soil concerning compaction due to different intensities of low, medium, and frequent machine passages. The current research aims to elucidate the process of restoring the compacted soil in condition of different intensities of compaction (low, medium, and frequent traffic) as a result of planting black alder in the skid trails. The results are observed 27 years after the logging operations ended. In this study, the hypothesis tested is that the restoration of litter and soil properties following compaction and subsequent black alder planting in the skid trails shows a significant difference among the various intensities of machine passages.

2 | MATERIALS AND METHODS

2.1 | Site description

The experimental site was placed in compartment no. 633 in the Tyrumrud forested watershed, near the Tonekabon city in the Hyrcanian forests, northern Iran (Figure 1a–c). The climate of the study site is humid. The annual precipitation in the study area is 1090 mm. The altitude of the study area ranges 440–480 m above sea level facing a northeastern aspect. The mean annual temperature is 12.9°C, with July (21.8°C) and February (−1.9°C) having the highest and lowest monthly temperatures, respectively. The soil of the experimental site is Alfisols, which is located on the limestone and dolomite limestone based on the USDA soil taxonomy, and the soil texture is clay loam (the percentage proportion of sand; 24.3%, silt; 37.7%, clay; 38.0%). The experimental site is severely degraded due to fuelwood harvesting by rural communities and also cattle grazing before clearcutting and reforestation in 1995. The intact stand in the experimental site was previously prevailed by a deciduous tree species stand of hornbeam (*Carpinus betulus* L.)—ironwood (*Parrotia persica* C.A.M.), with chestnut-leaved oak (*Quercus castaneifolia* C.A.M.), black alder (*Alnus glutinosa* (L.) Gaertn.), and Velvet maple (*Acer velutinum* Boiss).

The degraded forests of the study area were clear-cut and prepared to be reforested in 1995 by the Natural Resources and Watershed Management Organization (NRWMO). Theoretically, it would have been preferable to include black alder with no traffic as a control for this study, but other local tree species, hornbeam—ironwood (CB-PP), were chosen as a control. The study area was chosen in consideration that the clear-cutting was mostly covered with the CB-PP species. The comparison of the compaction recovery due to black alder planting with the natural characteristics of control soil was also taken into account. The seedlings of black alder were planted in the clear-cut area with a space of 2 × 2 m. The treatments in the current study included a 27-year-old stand of black alder, where an undisturbed stand of hornbeam—ironwood (CB-PP) positioned alongside the planted stand was chosen as the control (Figure 1d).

Trees in the study area were cut, delimbed, and bucked using chainsaw, and the logs with a length of 3–10 m were skidded by TAF E655 cable skidder in July 1995. TAF E655 cable skidder main attributes are mentioned in Jourgholami et al. (2019,b).

2.2 | Experimental design

Four skid trails, planted with black alder, were selected in this study area (Figure 1c,d). In each skid trail, three traffic intensities (low, medium, and frequent machine passages) were selected based on forestry plan documentation and distance from the landing. A sample plot was implemented with a 4 × 10 m dimension at each intensity. The class of low machine passages included skid trails which had <3 skidding cycles, medium machine passages had 3–10 skidding cycles, and frequent machine passages had >10 skidding cycles. In this plot, five measuring lines 2 meters apart plus other three lines were randomly selected. On each line, two 20 × 20 cm locations were considered for sampling, with one sample in the center of the right wheel track and the other in the center of the left wheel track at a depth of 0–10 cm. For the control area, the intact area of the hornbeam—ironwood (CB-PP) stand was selected and four plots with 4 × 10 m and six soil samples were measured in each plot (Figure 1d) (Table 1).

2.3 | Data collection and laboratory analysis

To analyze litter properties in each sampling position, litter was gathered at the area of 20 × 20 cm, placed in bags, transferred to the laboratory, and dried at 70°C for 48 h to a constant weight, and then analyzed. A tape measure was used to measure litter thickness with millimetric precision. The CN elemental analyzer (Perkin Elmer, U.S.A 2400 Series II) (Hättenschwiler & Jørgensen, 2010) was used to determine the C and N of litter. To measure the soil bulk density and soil moisture, soil cores were sampled at the topsoil by employing a thin-walled steel cylinder (length = 10.0 cm, radius = 2.80 cm). The samples were weighed with gram precision, put in the bags, marked, transferred to the laboratory, and oven-dried at 105°C for 24 h. To specify soil characteristics, the collected samples were separated into two sections: one section of the sample was gathered at the profile of 20 × 20 × 10 cm, air-dried, and moved through a 2-mm sieve to

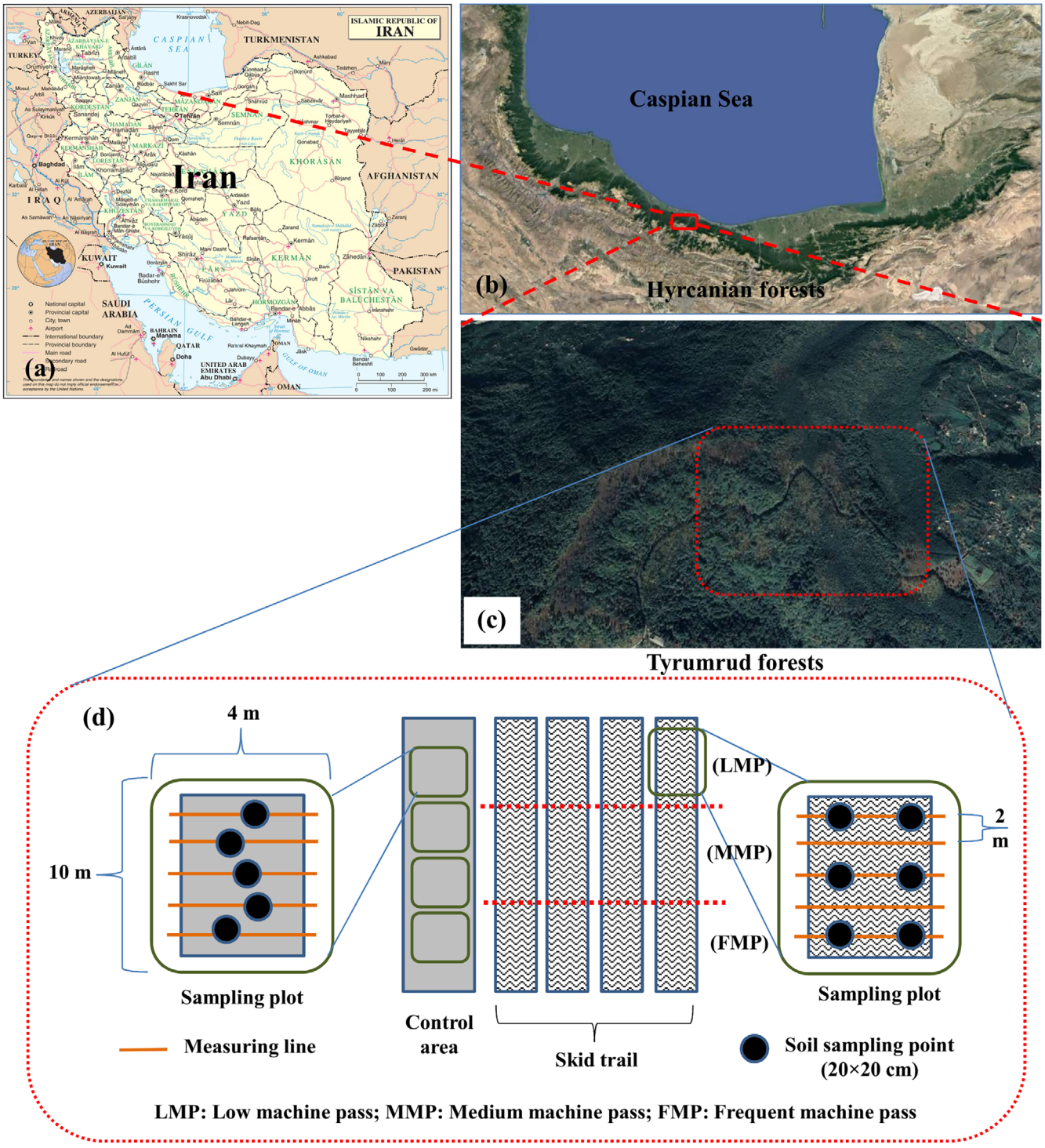


FIGURE 1 Location of the experimental site in Northern Iran (a) in the Hyrcanian forest (b), and Tyrumrud forests (c). An illustrative diagram of the test design on the skid trails in each treatment (d). [Colour figure can be viewed at wileyonlinelibrary.com]

analyze soil physical and chemical properties. To measure the soil texture (distribution of clay, silt, and sand), the hydrometer method (Gee & Bauder, 1986) was used. The water desorption method (Danielson & Southerland, 1986) was applied to measure the macroporosity. To specify the resistance to penetration (PR), the analog hand-held soil penetrometer (with a 60° cone, four types of cones; 1, 2, 3.3, and 5 cm^2) was used. The wet sieving method (Kemper & Rosenau, 1986) measured the aggregate stability. Total porosity was determined by applying Equation (1).

$$TP = 1 - \frac{\frac{M_s}{VC}}{2.65} \times 100 \quad (1)$$

TABLE 1 The treatment attributes (average ± std) in the experimental site. MP = Machine Passage on skid trails in plantations of black alder (*Alnus glutinosa* (L.) Gaertn.).

Treatment	Main species	Slope (%)	Aspect direction[a]	Tree density (N ha^{-1})	Growing stock (m^3 ha^{-1})	DBH (cm)
CB-PP	Hornbeam (*Carpinus betulus* L.) – ironwood (*Parrotia persica* C.A.M.)	17.00 ± 1.00a	Northeast	309.40 ± 23.90c	263.50 ± 22.80b	52.70 ± 7.30a
Low MP	Black alder (*Alnus glutinosa* (L.) Gaertn.)	18.00 ± 4.00a	Northeast	592.60 ± 31.70a	272.60 ± 32.60a	18.60 ± 3.60b
Medium MP	Black alder (*Alnus glutinosa* (L.) Gaertn.)	15.00 ± 3.00b	Northeast	561.30 ± 37.50ab	247.10 ± 25.10bc	17.30 ± 2.60b
Frequent MP	Black alder (*Alnus glutinosa* (L.) Gaertn.)	13.00 ± 5.00c	Northeast	514.70 ± 27.40b	201.50 ± 27.40c	14.90 ± 3.20b

Note: Tree density is the average number of tree per hectare, and growing stock is the average tree volume per hectare, DBH is the diameter at breast height, when the analysis of variance (ANOVA) found the difference between the means of treatments; the significant differences in each treatment by Duncan's test ($p < 0.05$) were shown with different letters.
[a]The compass direction that the slope faces is the aspect.

where TP is the total porosity of soil (%), Ms is soil mass (g), VC is the soil core volume (246.30 cm^3), and 2.65 (g cm^{-3}) is the particle density as assumed for most soils.

After sieving, soil chemical properties were estimated as follows: The Orion Ionalyzer (Model 901) pH meter in a soil:water ratio of 1:2.5 was applied to specify soil pH. To specify soil organic C (Walkley & Black, 1934), the Walkley–Black technique was applied. To specify total N (Walkley & Black, 1934), the Kjeldahl procedure was applied. The soil storage of C and N at the 0–10 cm depth was calculated as Equation 2:

$$SOs\,(C\,or\,N) = C\,or\,N \times BD \times e \times 0.1 \quad (2)$$

where the SO s (C or N) illustrates the organic carbon (C) or nitrogen (N) storage in the soil layer (Mg ha^{-1}); C or N is the organic C or total N content (g kg^{-1}); BD is the bulk density (g cm^{-3}); e is the layer thickness (cm); and 0.1 is the conversion factor for soil depth.

The Olsen method with a spectrophotometer was performed to gauge the available phosphorous (P). An atomic absorption spectrophotometer (Kooch et al., 2014; Salehi et al., 2013) was performed to gauge available nutrients (potassium; K, calcium; Ca, and magnesium; Mg). The International Humic Substances Society (IHSS) method was performed to gauge soil humic acid and fulvic acid (Kooch et al., 2014). Manual sampling was performed at the samples position with the area of 25 × 25 × 10 cm, to measure the earthworm number and density (Salehi et al., 2013). To measure the earthworm dry mass, the earthworms were enumerated in the sample position, transferred to the laboratory, cleaned, oven-dried at 60°C for 24 h to attain the constant weight, and thereupon reweighed (Kooch et al., 2017,b). To specify the biomass of fine root, fine roots were segregated from the sample position and dried at 70°C (Neatrour et al., 2005). To apply the measuring of soil biological characteristics, another section of sampled soil was kept in bags at 4°C for further analysis. To measure soil microbial respiration, the CO_2 evolved in a 3-day incubation experiment was employed 25°C (Kooch et al., 2014). The chloroform-fumigation extraction procedure (Brookes et al., 1985) was performed to specify the microbial biomass carbon (MBC), nitrogen (MBN), and phosphorus (MBP). To extract soil NH_4^+ and NO_3^- via 2 M KCl solution (soil:solution, 1:5) (Yang et al., 2017), the colorimetric techniques were applied. To measure N mineralization (Robertson, 1999), the soil aerobic incubation was applied.

2.4 | Statistical analyses

The variables normality was checked using the Kolmogorov–Smirnov test and the variance equality was examined by Levene's test. The differences of the soil properties among various machine pass intensities and the undisturbed stand were shown by ANOVA when a normal distribution of data was achieved (all data were normally distributed). The Duncan multiple range test was applaied to examine the significant differences between the soil properties among different treatments and the undisturbed (control) area at $p \leq 0.05$. The Pearson correlation was used to examine the relationship between litter and soil properties. All statistical analyses were performed using SPSS Statistics for Windows, version 17.0 (Chicago, SPSS Inc.).

3 | RESULTS

3.1 | Litter properties

The treatments significantly affected litter properties (Figure 2). The highest values of litter thickness (Figure 2a) and percentage content in C (Figure 2b) and N (Figure 2c) of the litter were observed in the CB-PP stand, followed by the skid trail with low machine passages. The greatest value of litter C/N (Figure 2d) was detected in the skid trail with frequent machine passages. Results revealed that litter properties did not return to the pre-harvest level until a period of 27 years had passed from the termination of the skidding operations and planting (Figure 2).

3.2 | Soil physicochemical properties

The highest values of bulk density (BD), resistance to penetration (PR), soil moisture, and sand content were identified in the skid trail

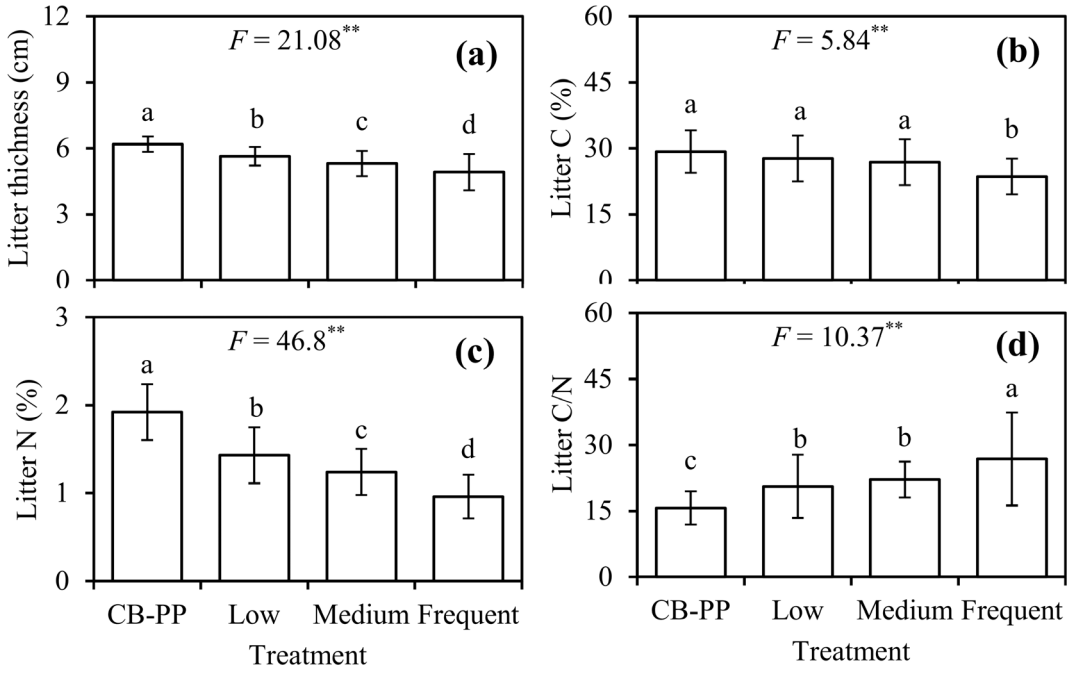


FIGURE 2 Average values (±std) of litter properties; litter thickness (a), litter C (b), litter N (c), and litter C/N (d) in the different treatments. *F*-values based on the ANOVAs are presented. ** show the significance value at $p < 0.01$. The significant differences in each treatment by Duncan's test ($p < 0.05$) were shown with different letters. MP = Machine Passage on skid trails in plantations of black alder (*Alnus glutinosa* (L.) Gaertn.

with frequent machine passages, while the lowest amount of these values was observed in the CB-PP natural stand (Table S1). The soil bulk density was higher in low MP than the value observed in the CB-PP by 11%. The values of total porosity, macroporosity, aggregate stability, silt, and clay were at the highest level in the CB-PP natural stand, followed by the skid trail with a level of low machine passages. The trend of changes in soil physical properties over a 27-year period revealed that these values were still higher in the planted skid trails, compared to the hornbeam-ironwood stand.

The highest values of soil pH, C, C/N ratio, and C storage were recorded under the skid trail with frequent machine passages, while the lowest amounts of these values were observed under the CB-PP stand. Furthermore, the values of N, N storage, and available nutrients (i.e., P, K, Ca, and Mg) were at the highest level at the CB-PP stand, followed by the skid trail with low machine passages. Results confirmed that the rehabilitation of the analyzed soil physicochemical properties requires more than 27 years to return to the original state. Although a period of 27 years had passed since the black alder was planted, the complete recovery of these properties had not yet occurred (Table S1).

3.3 | Soil biochemical and biological properties

Results show that the amounts of fulvic acid, humic acid, earthworm density and dry mass, fine root biomass, soil microbial respiration, microbial biomass carbon (MBC), ammonium (NH_4^+), nitrate (NO_3^-), N mineralization, microbial biomass nitrogen (MBN), and microbial biomass phosphorous (MBP) were found at the highest level under the CB-PP forest stand, followed by the skid trail with low machine passages, while the highest level of MBC/MBN and MBC/MBP were detected under the skid trail with frequent machine passages (Table S2). Earthworm density and dry mass, and fine root biomass was lower in low MP than the value observed in the CB-PP by 35%, 32%, and 18%, respectively. The remediation of the analyzed soil biochemical, biological, and microbial properties may require an amount of time which is longer than 27 years.

The results of the Pearson correlation showed that some litter and soil properties such as litter C/N, BD, PR, soil moisture, sand, pH, soil C, soil C/N, C storage, microbial biomass carbon, MBC/MBN, MBC/MBP, and MBN/MBP had negative relationships with other litter and soil properties. Also, earthworm biomass and density and fine root biomass has negative relationships with litter C/N, BD, PR, soil moisture, sand, pH, soil C, soil C/N, C storage, microbial biomass carbon, MBC/MBN, and MBC/MBP, and has positive relationships with litter C and N, TP, MP, AS, soil N, available nutrients (P, K, CA, and Mg) (Figure 3).

4 | DISCUSSION

4.1 | Litter properties

The most important source of organic carbon input to the forest floor is litter fall (Giweta, 2020; Krishna & Mohan, 2007). The litter of black alder has a high content of nitrogen and a very low C/N ratio. A lower

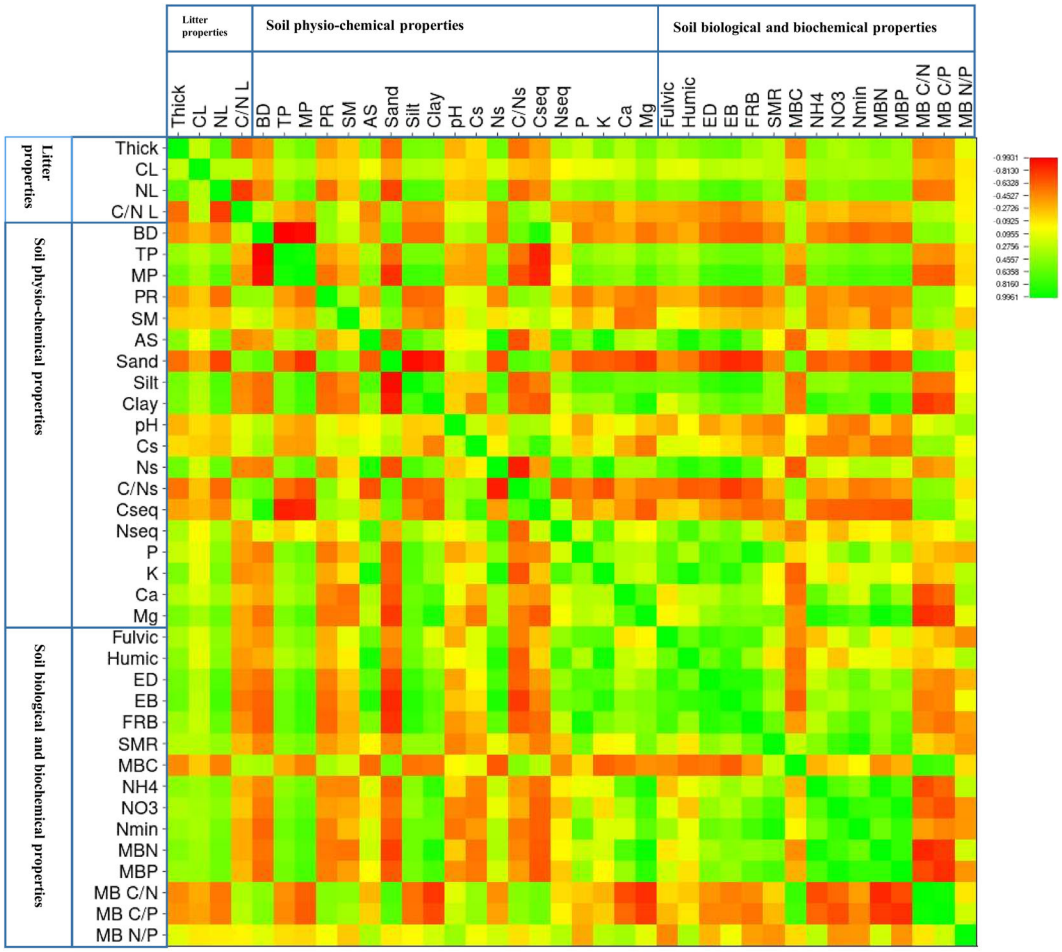


FIGURE 3 Pearson correlation (Heat map) between litter properties and soil properties in the different treatments. Litter properties (Litter T: litter thickness; CL: litter C; NL: litter N; C/NL: litter C/N ratio), soil physical (BD: bulk density, TP: total porosity, MP: macroporosity, PR: penetration resistance, MC: moisture content, AS: aggregate stability, sand, silt, clay), chemical (pH, EC, C: organic C, N: nitrogen content, C/N: C/N ratio, Cseq: C storage, Nseq: N storage, P: available phosphorous, K: available potassium, Ca: available calcium, Mg: available magnesium), biochemical and biological (EW: earthworm density, Ewb: earthworm biomass, SMR: soil microbial respiration, FRB: fine root biomass, Fulvic: fulvic acid, Humic: humic acid), C and N microbial properties (SMR: soil microbial respiration, MBC: microbial biomass carbon, NH_4^+: ammonium, NO_3^-: nitrate, N Min: nitrogen mineralization, MBN: microbial biomass nitrogen, MBP: microbial biomass phosphorous). [Colour figure can be viewed at wileyonlinelibrary.com]

C/N ratio in black alder litter is a prerequisite for the rapid decomposition of organic matter (Miletić et al., 2012). Litter deposition on the topsoil by cultivated trees is considered a nutrient source (e.g., litter, soil C) that is a major motivator of microbial activity (Althoff et al., 2009; Krishna & Mohan, 2007). In line with the findings of this study, previous studies show alterations in substrate and surface soil characteristics after planting with endemic and non-endemic plants, which are fundamentally related to the substrate quality (Jourgholami, Ghassemi, & Labelle, 2019; Jourgholami, Labelle, & Feghhi, 2019). Litter plays a key role in biomass turnover and energy flow between the soil surface and the subsurface layers. It is the main supplier of carbon and nutrient pools in forest stand (Chen et al., 2023). Following the planting of black alder, the substrate rehabilitates nutrients into the soil after organic matter mineralization and nutrient delivery. Furthermore, the dominant factors which control the rate of litter decomposition are litter and soil C/N ratio (Langenbruch et al., 2012; Vauramo & Setälä, 2011). Previous studies have indicated that labile compounds such as the litter of black alder with a high N, low lignin, C/N ratio, and low lignin/N ratio are the main drivers of litter decompostition (Althoff et al., 2009; Diao et al., 2020; Yang & Zhu, 2015).

4.2 | Soil physicochemical properties

Mechanized logging operations causing soil disturbance and compaction produce a significant change in the soil habitat leading to a decline in water infiltration (Althoff et al., 2009; Krishna & Mohan, 2007). In accordance with the findings of this study, it was shown that the traffic of skidding machines had negative effects on soil structure and dynamics. By increasing the intensity of machine traffic on the skid trails, soil bulk density increases logarithmically; in other words, the highest increase in soil bulk density occurs during

the first passes of the logging machine, and subsequent passes increase soil bulk density at a slower rate. However, every machine pass results in an increase in soil bulk density, which leads to an increase in soil compaction as reported in the previous studies (Labelle et al., 2022; Nazari et al., 2021). Litter layer performs a key function in governing the C and N cycles of plant and soil in the forest stands, and regulates soil microclimate by acting as a buffer between the soil surface and the atmosphere (Sayer, 2006). Clear cutting and subsequent reforestation clearly affect the primary net fertility of the forest and thus change the inputs of aboveground litter to the soil (Miao et al., 2019; Nazari et al., 2020; Sohrabi et al., 2022). Litter quality, soil microbial populations, soil fauna, and environmental elements are considered as the main stimuli of litter decomposition, which significantly plays a key role in the recovery of soil bulk density (García-Palacios et al., 2013). Some phenomena including shrinkage via water extraction and development of macropores due to root penetration and propagation are the positive effects of the roots of seedlings to improve and restore the physical structure of compacted soils (Flores Fernández et al., 2017, 2019; Jourgholami, Ghassemi, & Labelle, 2019; Meyer et al., 2014; Warlo et al., 2019). The natural recovery of compacted soil can occur due to the shrink–swell phenomenon of claish soils and the freeze–thaw cycles (DeArmond et al., 2021; Nazari et al., 2021). The natural reclamation of soil properties following machine traffic may need a period of time that ranges from a number of years to many decades (DeArmond et al., 2021; Flores Fernández et al., 2017; Meyer et al., 2014; Nazari et al., 2021). Some factors such as soil types, soil textures, degree of soil compaction, soil depth, climates, and fauna can affect the amelioration of compacted soils (DeArmond et al., 2021; Labelle et al., 2022; Mohieddinnea et al., 2019). However, in recent years, the planting of the seedlings of suitable species to hasten the regeneration of the soil structure has been expanded and has achieved positive results (Flores Fernández et al., 2017; Jourgholami, Ghassemi, & Labelle, 2019; Meyer et al., 2014; Nazari et al., 2023; Warlo et al., 2019). Black alder plantation was previously reported to produce significant results in restoring soil structure and augmenting soil aeration (Sroka et al., 2018). Similarly, Meyer et al. (2014) showed that the roots of alder trees initiate soil structure improvement by creating pores. Their study highlights that tree root growth can considerably accomplish the recovery of soil structure after compaction.

Black alder (*Alnus glutinosa*) like other alder species (*Alnus* sp.) is in symbiosis with nitrogen-fixing actinomycetes of the genus *Frankia*, which enriches soil via nitrogen (Sroka et al., 2018). Hence, introducing black alder on the degraded forest area can enhance organic matter content and improve soil nitrogen-fixing bacteria which need a considerable amount of carbon (energy) for nitrogen-fixation, that may consume the soil's carbon reserves in the soil (Beaupied et al., 1990). However, black alder root exudates can supply the bacteria with adequate energy for nitrogen-fixation, leading to reduced soil organic carbon (SOC) content as well (Abdel-Lateif et al., 2012). The litter of black alder has a high amount of nitrogen, leading to fast mineralization (Warlo et al., 2019). Similarly, Li et al. (2020) demonstrated that the leaf litter can regulate SOC as well as influence nutrient transport. The amount of potassium, calcium, and magnesium in black alder litter is considerable, as are nitrogen and phosphorus (Miletić et al., 2012). The partial recovery of the soil properties in the skid trails, especially in low and medium machine passages, can be promoted by the biochemical and physical quality of alder litter. Results of the current study showed that litter C and N significantly augmented after black alder planting in the skid trail, especially in the trails with low machine passages. Various studies have expressed positive effects of planting alder on the restoration of soil organic matter and N content compared to other tree species (Augusto et al., 2002; Hoogmoed et al., 2014; Kooch et al., 2016, 2017,b; Sroka et al., 2018; Xiong et al., 2014). Our findings are also consistent with Sroka et al. (2018), declaring that the higher organic C can be attributed to the larger biomass and litter production of black alder planted in the skid trails. Soil pH, total N, available P, Ca, and Mg, earthworm density/biomass, and soil microbial respiration were significantly superior under the canopy of alder as compared to that of other species (Augusto et al., 2002; Kooch et al., 2016). Our results have shown that the lower soil pH in the trail with low machine passages can be related to the N-fixation process by black alder, which resulted in an increase in release of H^+ in the zone of root growth and activity as stated by Bolan et al. (1991), Rothe et al. (2002), and Chen et al. (2019).

4.3 | Soil biochemical and biological properties

Soil fauna mixes the mineral part with the organic matter, alters water infiltration and water regime, which lead to stimulate the microbial communities, and these in turn hasten the decomposition processes (Giweta, 2020). Earthworms play a fundamental role by ingesting soil organic matter, altering the dynamics of soil nutrients, and improving the structures of the soil, sustaining the cycle of nutrients, and the fertility of the soil (Ruiz et al., 2008). In this study, the earthworm indics were boosted in areas planted with black alder, which can be attributed to the quality of litter including the lower C and C/N ratio, greater N, and nutrient availability (Jourgholami et al., 2021; Jourgholami, Ghassemi, & Labelle, 2019; Jourgholami, Labelle, & Feghhi, 2019). Another factor that helps the mineralization of nutrients is the existence of fine roots. Some studies stated that roots play an important role in phosphorus mineralization, in some cases even more than litter (Uselman et al., 2012; Yano et al., 2005). The inorganic phosphate or available phosphorus can be absorbed by fine roots. However, the usage of phosphorus is highly dependent on the activities of extracellular enzymes or organic acids in soil (Li et al., 2022). Plants have employed several strategies for the uptake of phosphorus by altering root structure and modifying the soil chemical properties in the rhizosphere (Pantigoso et al., 2020).

Similar to our results, previous studies affirm that soil under black alder is biologically more active, which maintains higher microbial biomass, leading to more respiration as compared to other tree species (Flores Fernández et al., 2017; Jourgholami, Ghassemi, & Labelle, 2019; Jourgholami, Labelle, & Feghhi, 2019; Šnajdr

et al., 2013). Similar to our results, Liu et al. (2021) concluded that litter decomposition rapidity was positively associated with the NO_3^-, NH_4^+, and MBN concentrations. The litter decay rate and mineralization were substantially affected by litter quality (Giweta, 2020). The availability and quality of carbon and nutrients in soil influences soil microbes, thereby litterfall after planting significantly affects soil microbial biomass (Feng et al., 2022). However, Nazari et al. (2020) reported that re-compaction have no significant effects on the soil organic C and total N contents. Results of the current study showed that planting black alder trees in the skid trails leads to improved soil microbial properties. Similarly, Demoling et al. (2008) affirmed that water availability and N accumulation are the crucial regulating factors of soil microbial properties, which significantly enhance the growth and activity of soil microorganisms. The physiological abilities of soil microbial populations are impacted by the quality of organic matter content. Since the black alder litter consists largely of labile organic compounds that contain high N and less lignin, it is more easily decomposable than litters of other species. Soil microbial respiration in forest stand is affected by several factors including moisture content, soil nitrogen content, litter quality, organic matter content, and tree cover (Flores Fernández et al., 2019; Langenbruch et al., 2012; Meyer et al., 2014). In a forest stand with different degrees of soil compaction, changes in soil particle size distribution can affect the soil microbial respiration rate. Usually in soils with more sand, the soil respiration rate decreases (Giweta, 2020). In skid trails with medium and frequent machine passages, the amount of sand was significantly greater than in other treatments, which was effective in reducing soil respiration. Soil respiration was mainly generated by soil microorganism and plant roots. Soil respiration was consistently higher on the fine- versus coarse-textured soil. Since, coarse-textured soil has low SOM content, and less moisture, hence, soil respiration rates are also in a lower level compared to fine-textured soil (Cable et al., 2008).

The amount of soil respiration may also change due to soil moisture (Perez-Suarez et al., 2012). The presence of sufficient moisture in the soil of skid trails after alder planting provides a suitable environment for the activity of soil microorganisms and increases their activity, thereby increasing soil respiration. Accordingly, increasing the C/N ratio of soil in the compacted forest soil results in a decline in the amount of respiration emitted from the soil. The higher rate of soil microbial respiration in the hornbeam-ironwood stand and skid trail with low machine passages can be attributed to the increase in soil nutrients (nitrogen, phosphorus, and potassium). These stimulate the activity of soil microbes leading to an increase in soil microbial respiration. Microbial biomass is a substantial element in forest stands, which can have a significant effect on the nutrient availability for trees. This characteristic is closely related to the soil fertility and health and can be considered as a useful ecological indicator to evaluate the stress caused by the destruction created by soil compaction. The findings of our study demonstrated that after soil compaction, the microbial biomass (C, N, and P) decreased significantly, which could be a result of the enhancement in the soil bulk density and the decline in the litter input. In addition, the soil particle size distribution, particularly the amount of clay, plays an indispensable role in determining the microbial activity. Hence, soils with higher amounts of clay in the control treatment and the skid trail with low machine passages lead to more nitrogen accumulation in the microbial biomass.

A substantial increase in nitrogen due to both the decomposition of black alder litter and the coexistence of alder roots with nitrogen-fixing bacteria caused an increase in microbial biomass, especially the microbial biomass nitrogen in the soil layer of skid trails planted with black alder. The existence of a negative relationship between microbial biomass and soil C/N ratio indicated the role of high C/N ratio in the soil of degraded skid trails in reducing soil microbial biomass (Bottinelli et al., 2014). Accordingly, microbial biomass is a key index to assess the alterations in soil fertility because it reacts to change in soil quality faster than the soil chemical characteristics (Giweta, 2020; Lucas-Borja et al., 2019; Meyer et al., 2014). Changes in soil ammonium and nitrate concentrations in skid trails, especially medium and frequent machine passages, can be affected by processes such as leaching or increased plant absorption due to the aging of black alder trees planted in skid trails.

5 | CONCLUSION

This study shows the effectiveness of planting black alder to restore the compaction-induced soil properties. Skid trails with three intensities of machine passages (low, medium, and frequent) were tested after 27 years and compared to the natural stand of hornbeam–ironwood in the mixed broadleaf forest. The highest recovery values of soil physicochemical, biochemical, biological, and microbial were recorded under the skid trail with low machine passages, followed by medium and frequent machine passages. The results showed that black alder as N-fixing tree species partially recovered the soil properties, with high quality litter (high N and less litter and soil C/N ratio) that significantly contributed to soil microbial C and N biomass and activity in the skid trail with low machine passages during a 27-year period. These findings show that soil physical, chemical, biological, and microbial properties were not fully restored after a 27-year period in the skid trail with three levels of compaction due to machine passages, and these values were lower than those observed in the hornbeam-ironwood undisturbed stand. The results of this study give clear evidence of the positive effects produced by black alder to restore soil properties after the soil disturbance caused by compaction. Black alder is a light-loving and fast-growing tree. Its root changes with the condition of the soil in such a way that in moist soils it is usually shallow, but in low water soils, the root sinks deep into the soil to get access to the water it needs. The black alder is able to fix atmospheric nitrogen in the soil, and considering that this species plays a role in providing soil nitrogen and can be grown along with other important species, it is important in reforestation programs. Also, considering the need to cope with climate change and adapt to global warming, black alder plays a crucial role in soil carbon sequestration due to its higher C storage in forestlands.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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