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Assessment of Variability among Humus Forms and Soil Properties in Relation to Tree Species and Forest Operations in the Kheyrud Forest, Nowshahr

Hadi Sohrabi [1], Meghdad Jourgholami [1], Rachele Venanzi [2] and Rodolfo Picchio [2,*]

[1] Department of Forestry and Forest Economics, Faculty of Natural Resources, University of Tehran, Karaj 999067, Alborz, Iran
[2] Department of Agricultural and Forest Sciences, University of Tuscia, Via San Camillo de Lellis, 01100 Viterbo, Italy
* Correspondence: r.picchio@unitus.it; Tel.: +39-0761357400

Abstract: Tree species and litter play a key role in the functioning of forest ecosystems as influential factors affecting soil ecological processes and the distribution of humus forms. This study investigates the morphology of humus under the litter of different trees on compacted skid trails at different time intervals after skidding operations (6, 10, and 20 years) in the Kheyrud forest, Nowshahr. Each skid trail was identified with three replications in pure beech, beech-hornbeam and mixed beech stands and a total of 81 profiles with dimensions of 30 × 30 cm, drilled and classified using the European Humus Group Proposal (EHGP). According to the results, the mull of the most dominant humus was under the mixed beech litter, while in the pure beech litter the amphi humus was the most abundant form of humus. Three types of humus mull, moder, and amphi were observed in the skid trail under the beech-hornbeam litter. Oligomull was the most abundant form of humus mull in the skid trail under mixed beech litter, while in the trails under pure beech Eumacroamphi, Eumesoamphi, and Hemimoder were the most common forms of humus amphi and moder. Also, the thickness of the organic layer (Organic litter, Organic fragmentation, and Organic humus) was higher in all skid trails under the pure beech litter as compared to other treatments, while from younger trails (6 years) to older trails (20 years), the thickness of the organic-mineral horizon (Ah) increased under the beech mixed litter. We can conclude that different litter types were the main factor to control the presence of different forms of humus after forest operations.

Keywords: Hyrcanian forests; humus classification; organic horizons; skidding operations; tree litter

Citation: Sohrabi, H.; Jourgholami, M.; Venanzi, R.; Picchio, R. Assessment of Variability among Humus Forms and Soil Properties in Relation to Tree Species and Forest Operations in the Kheyrud Forest, Nowshahr. *Forests* **2022**, *13*, 2156. https://doi.org/10.3390/f13122156

Academic Editor: Miriam Fernanda Rodrigues

Received: 22 November 2022
Accepted: 14 December 2022
Published: 16 December 2022

1. Introduction

Damage to the forest floor is considered one of the most serious and unavoidable disturbances resulting from forest harvesting operations [1]. The change of organic matter as a part of the surface solid compounds of the soil and its effect in improving the physico-chemical and fertility properties of the soil are very important [2–4]. Humus is a part of surface soil that is affected by biological elements, such as the amount of litter and its quality, macro- and micro-organisms living in the soil, and abiotic elements which include climate, management type, bedrock, and soil type [5,6]. Forest management, such as harvesting operations, has a direct and indirect effect on some of these factors and plays a role in the variability of humus form.

The humus forms are created in a shorter period of time than the mineral soil type that needs independent classification [6,7]. Compared to the soil, the humus form is more sensitive to changes in plant growth, canopy cover, tree species, and management, therefore, by describing and examining humus forms, it is possible to understand short-term changes in the forest [2,6,8]. Furthermore, humus forms are considered a morphological pattern in relation to organic and mineral substances, and as a driving force, it shows many changes in forest ecosystems [9,10]. In addition to maintaining soil moisture and nutrient elements, soil humus reduces soil erosion due to the interception of throughfall kinetic energy in high altitudes by creating a suitable bed [9,11]. Humus provides a convenient ambient for the interactions between plants, macro-, and micro-organisms and thus accelerates the process of decomposition and nutrient cycling, which are pivotal in forest ecosystems [3,5,12].

Due to the effect of the litter quality and the decomposition rate in the formation of humus forms, forest species and their effect on the types of humus are imperative to maintain equilibrium [4,10,12]. The close relationship between the humus form, forest cover, and soil makes the humus type considered one of the constant components of the forest floor [2,8]. The humus morphological study is preferred over chemical methods due to low cost, simpler methods and tools [3,10,13]. In the Hyrcanian forests of Iran, Sajedi et al. [14] conducted the first study on the identification of humus forms in pure and mixed beech stands of these forests. The results of this study using the Canadian classification [15] showed that under the influence of the type of forest stand, the humus forms of mull and moder were studied in the forest stands. Andreetta et al. [16] in a review study on humus forms in Italy stated that tree species play an important role in predicting the type of humus form. By using the European Humus Group Proposal [6], Bayranvand et al. [4] observed most of the humus systems, including mole, muder, and amphi under the influence of different altitude classes and six different forest stands.

The review of previous literature confirmed that the type of forest management is one of the factors affecting the variations in humus form [8,10,16,17]. Morphological studies have investigated humus forms and forest floor characteristics under the influence of different tree stands along elevation changes [4,17], but so far it has not been investigated in the forest area with a close focus on forest operations. In this study, the humus morphology was investigated in relation to the physical and chemical properties of the soil under the influence of the litter of different tree species (three stands of beech, beech-hornbeam, and mixed beech) on skid trails in different time intervals after harvesting operations. In general, the current research is aimed at finding answers to two questions: (1) Can the morphological characteristics of humus forms change under the influence of different tree litter and different time intervals in terms of years after harvesting operations? (2) Is there a close relationship between different tree litters, soil characteristics, and humus morphology? We hypothesized that: (1) the change in the type of litter of different tree stands affects the pattern of humus forms and the thickness of the organic layer and (2) in different years after logging operations, the humus form changes in relation to soil properties.

2. Materials and Methods

2.1. Site Description

The present research was carried out in the second (Namkhaneh) and third (Gorazbon) sections of the Kheyrud educational-research forest of Tehran University located in Nowshahr city in the north of Iran (36°34′21″–36°33′34″ N and 51°36′50″–51°38′21″ E) (Figure 1). The Hyrcanian forests of Iran belong to the Paleogene period as one of the most valuable forests in the world. These forests have been managed in the form of restoration, development and harvesting plans for the past half-century. The studied areas with an area of 2082 ha are located at approximately 1000 to 1360 m a.s.l. The average amount of rainfall in the studied area is 1146 mm according to the statistics of Nowshahr meteorological station. The average annual temperature is 8.6 °C with very hot and humid summers and cold winters. The studied area is located on limestone bedrock with Alfisol soil, which varies in soil texture from clay to clay loamy. According to previous studies, the most abundant humus form in pure and mixed beech stands is the mull and amphi humus system in Hyrcanian forests, respectively [10,18]. Kheyrud forest is mainly covered with a combination of beech (Fagus orientalis Lipsky), hornbeam (*Carpinus betulus* L.) and other species including Cappadocian maple (*Acer cappadocicum* Gled), Caucasian alder (*Alnus subcordata* C.A.M.), Date-plum (*Diospyrus lotus* L.), common ash (*Fraxinus excelsior* L.), ironwood (*Parrotia persica* C.A.M.), large-leaved lime tree (*Tilia platyphyllos* Scop.), and mountain elm (*Ulmus glabra* Hudson). The herbaceous species such as *Asperula odorata* L., *Euphorbia amygdaloides* L., *Hypericum an-drosaemum* L., and *Oplismenus undulatifolius* (Ard.) Roem. & Schult., and *Polystichum sp.* form the vegetation of the forest floor. The age composition of forest stands in this area is uneven-aged due to silvicultural treatments. The last effect of logging operations on the soil dates back to 6 years before the time of the study. Other required information about forest stands is listed in Table 1.

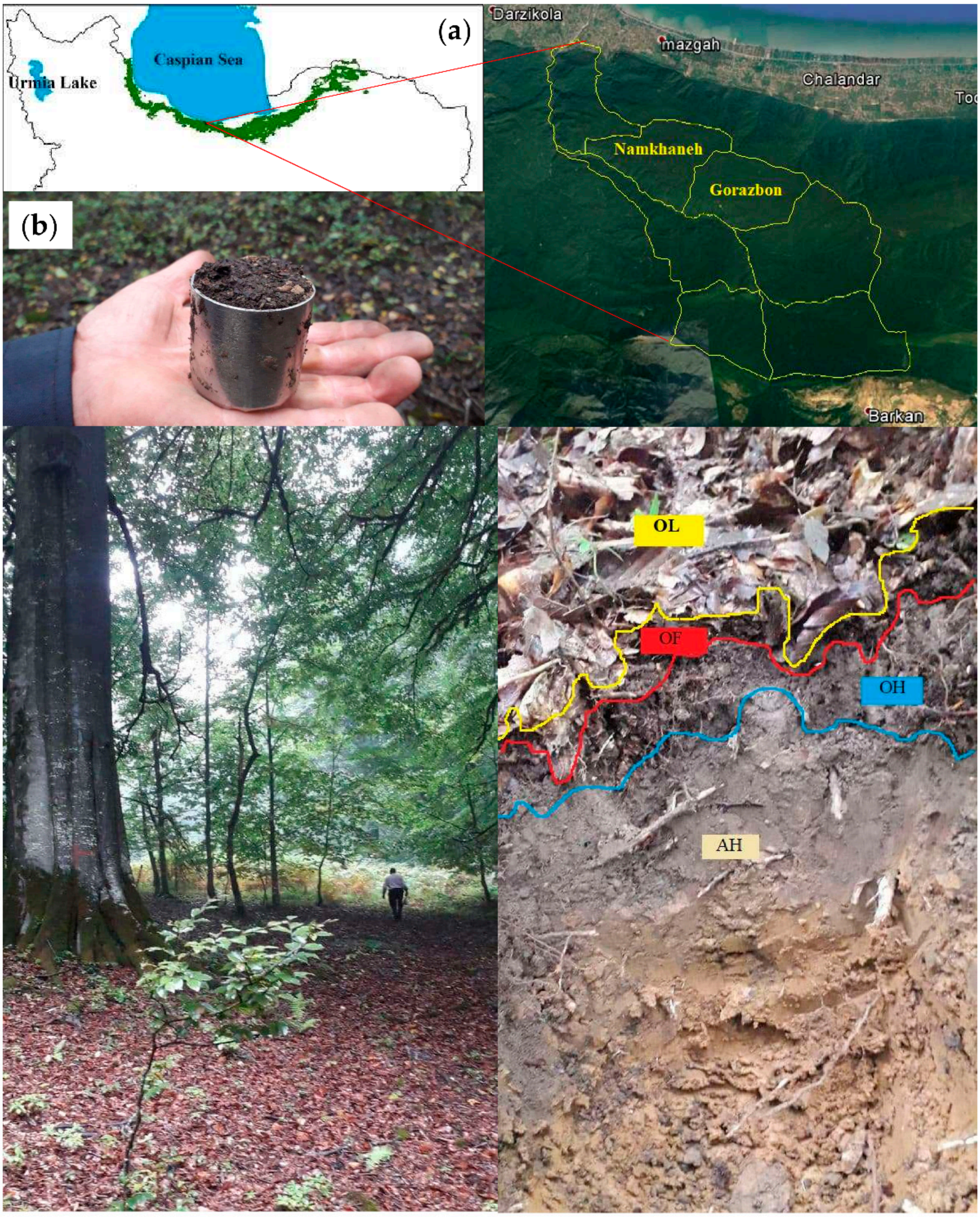


Figure 1. Study area (Namkhaneh and Gorazbon districts of Kheyrud forest) in northern Iran (**a**), Skid trails in each of the forest stands, soil profile and soil samples with metal cylinder (**b**).

Table 1. The characteristics of each of the forest stands and skid trails. B: (beech); B-H: (beech, hornbeam); B-H-O: (beech, hornbeam, Cappadocian maple, Caucasian alder, large-leaved lime tree and mountain elm).

Age of Skid Trail (Years)	Forest Stand (Main Species)	District (No. of Compartments)	Skid Trail Length (m)	Elevation (m a.s.l)	Tree Density (N ha^{-1})	Soil Texture
6	B	Gorazbon (C. 315)	255	1209	510	Clay
	B-H	Gorazbon (C. 316)	374	1174	496	Clay
	B-H-O	Gorazbon (C. 318)	310	1177	565	Silt clay loam
10	B	Gorazbon (C. 319)	240	1246	505	Clay
	B-H	Gorazbon (C. 320)	247	1345	520	Clay
	B-H-O	Gorazbon (C. 318)	360	1133	544	Silt clay loam
20	B	Namkhaneh (C. 215)	200	1040	495	Clay
	B-H	Namkhaneh (C. 220)	210	1115	482	Silt loam
	B-H-O	Namkhaneh (C. 214)	180	1010	510	Clay loam

2.2. Experimental Design

To achieve the objectives of the research, three forest stands (beech: B, beech-hornbeam; B-H, mixed beech: B-H-O) were identified based on tree species and litter type. In each of the forest stands, three skid trails with different time intervals of logging operation (6, 10, and 20 years) with three replications were identified. According to the study of Sohrabi et al. [19], three classes of high, medium and low traffic intensity were identified in each of the skid trails. (Figure 2).

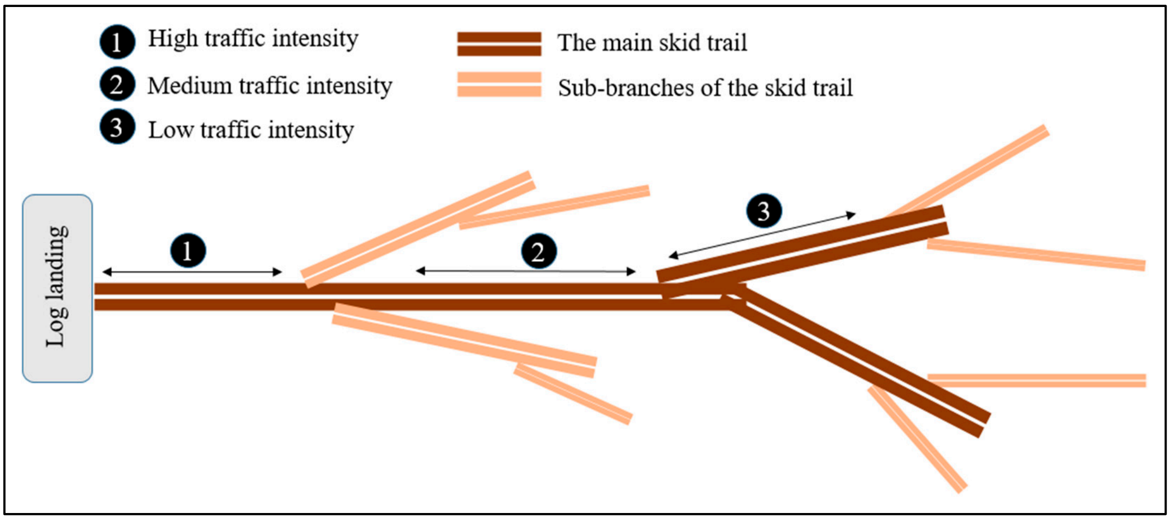


Figure 2. Skid trail with different traffic intensities.

To collect soil samples in each skid trail, sampling plots were designed with dimensions of 40 m^2. In each sample plot, three measurement lines were identified, and soil sampling was performed on the right and left wheel tracks at a depth of 0–10 cm. To collect the soil sample in the undisturbed area (54 samples for each time period), and to remove the effect of logging operations on the soil, a distance of 20–30 m was determined from skid trails. A total of 216 soil samples were collected with a combination of treatments of skid trail age, litter type and traffic intensity. Due to the influence of soil samples from climatic factors and humidity conditions, soil samples were collected in the dry season (one-month duration).

To determine the humus form and measure the litter thickness in each traffic class, three profiles with dimensions of 30 × 30 cm were taken on the skid trail, so 27 profiles were taken in each skid trail with three repetitions in the forest types. In the location of each of the profiles, the thicknesses of the diagnostic horizons were identified visually or with a 5–10× magnifying hand lens [20]. Each humus profile was classified according to the European Humus Group Proposal [6] on the basis of the morphological characteristics of the organic and/or organic-mineral diagnostic horizons. The study and sampling of the layers of organic matter and humus were done at the end of the growing season, i.e., December 2021.

2.3. Data Collection and Laboratory Analysis

After removing the litter layer from the soil surface, for some soil properties, soil samples were collected using a steel cylinder (5 cm in diameter and 10 cm in height, for a volume of 196.25 cm^3) from a depth of 10 cm. The wet weight of the soil samples was measured and coded before being transported to the laboratory. In the laboratory, the soil samples were dried at 105 °C for 24 h to calculate the soil moisture content, dry bulk density, and porosity. The soil texture was determined using the Bouyoucos hydrometric method [21]. Bulk density (BD, g cm^{-3}) was calculated using Equation (1).

$$\mathrm{BD} = \frac{\mathrm{WD}}{\mathrm{VC}} \tag{1}$$

where BD is the dry bulk density (g cm^{-3}), WD is the weight of the dry soil (g), and VC is the volume of the cylinder (cm^3).

Total soil porosity (TP; %) was calculated using Equation (2).

$$\mathrm{TP} = 1 - (\mathrm{BD}/2.65) \times 100 \tag{2}$$

Also, in each sampling location inside the designed plots, 2 kg soil samples were taken to measure some soil chemical properties. The Orion Ionalyzer (Model 901, Cambridge, MA, USA) pH meter was used to measure soil pH in a soil/water ratio of 1:2.5. Organic C was measured using the Walkey-Black method [22] and total N using a semi-micro-Kjeldahl method [23].

2.4. Statistical Analyses

SPSS version 20 software was used for statistical analysis. Kolmogorov–Smirnov (α = 0.05) and Levene's test (α = 0.01) were used to check the normality of data distribution and homogeneity of variance between treatments. The difference or lack of difference in the values of humus layer thickness (HLT) and soil physico-chemical properties under the influence of litter type treatments (forest stands) and skid trail age was investigated by one-way analysis of variance (ANOVA). Duncan's test ($p < 0.05$) was used for multiple comparisons of means. The abundance of humus forms in relation to the litter type treatments and skid trail age were checked for statistical significance by the chi-square (Fisher's exact) test. Pearson's correlation analyses were performed to correlate the forest floor and soil characteristics under the influence of litter type treatments and skid trail age. For non-normally distributed data, Spearman's correlation analysis was performed. Multivariate analysis based on principal component analysis (PCA) was used to determine the relationship and correlation between all the characteristics under investigation of the treatments [24].

3. Results

The results of the analysis of variance showed that different types of litter have a significant effect on the thickness of the humus layer (organic litter, organic fragmentation, organic humus and organic-mineral layer), forest floor properties (N and C/N ratio), soil physical properties (moisture and total porosity) and soil chemical properties (pH, C, N and C/N ratio) and has a significant and positive correlation with them (Table 2). However, the effect of different types of litter on bulk density ($p < 0.001$; $R = -0.60$) and soil C ($p < 0.001$; $R = -0.77$) analysed by Pearson's test is significant but it has a negative correlation with them.

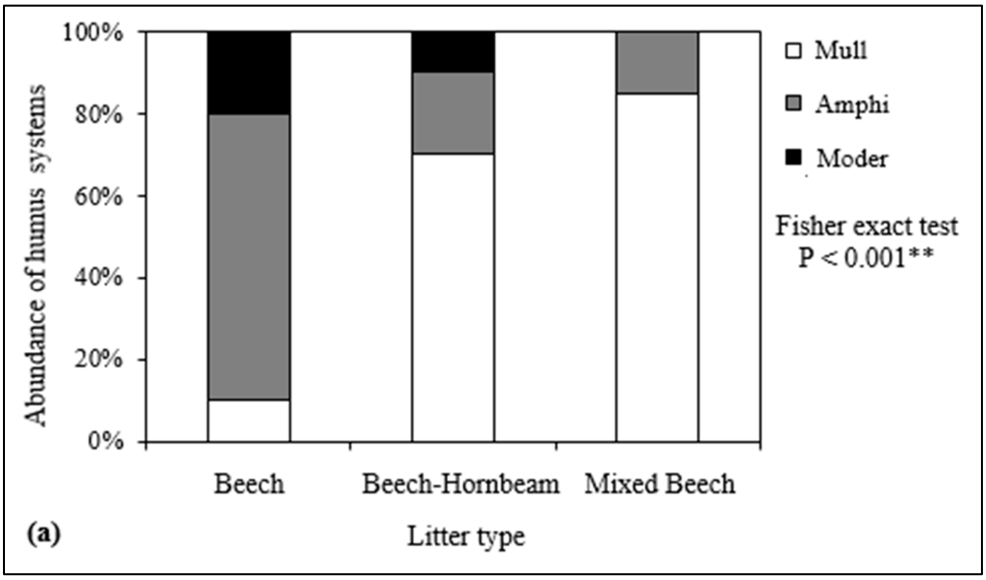
Table 2. One-way analysis of variance (ANOVA) and Pearson's correlation coefficients (R_{cor}) of forest floor and soil properties under the influence of litter type treatments (forest stands) and skid trail age. (*): $p < 0.05$; (**): $p < 0.01$.

			Litter Type (Forest Stands)			Age of Skid Trail		
Humus and Soil Properties	**Variables**	**Abbreviation**	**F Test**	***p* Value**	**R_{cor}**	**F Test**	***p* Value**	**R_{cor}**
Humus layers thickness	Organic litter (cm)	OL	70.22	<0.001	0.62 **	25.30	<0.001	0.66 **
	Organic fragmentation (cm)	OF	52.44	<0.001	0.75 **	33.62	0.021	0.36 *
	Organic humus (cm)	OH	15.16	<0.001	0.38 *	10.23	0.015	0.34 *
	Organic-mineral layer (cm)	AH	8.97	0.001	0.65 **	4.22	0.056	0.15
Forest floor properties	Forest floor carbon (%)	FFC	140.41	0.001	−0.82 **	156.6	<0.001	0.44 **
	Forest floor nitrogen (%)	FFN	128.5	<0.001	0.85 **	154.7	<0.001	−0.55 **
	Forest floor C/N	FFC/N	12.64	0.011	0.70 **	113.6	<0.001	0.33
Soil physical properties	Soil moisture (%)	SM	34.66	<0.001	0.66 **	90.05	<0.001	−0.62 **
	Bulk density (g cm^{-3})	BD	711.25	<0.001	−0.60 **	149.9	<0.001	0.58 **
	Total porosity (%)	TP	714.8	<0.001	0.55 *	140.4	<0.001	−0.47 **
Soil chemical properties	Soil pH	pH	1.16	<0.001	0.48 **	603.2	<0.001	−0.39 *
	Soil organic carbon (%)	SOC	1.19	<0.001	−0.77 **	2.91	<0.001	0.66 **
	Soil nitrogen (%)	SN	1.86	<0.001	0.79 **	720.8	<0.001	−0.71 **
	Soil C/N	SC/N	1.69	<0.001	0.59 **	1.252	<0.001	0.42 *

Among the characteristics of the Humus layers thickness, forest floor properties, and soil physical and chemical properties, the age of the skid trail has no significant effect and correlation only on the organic-mineral layer (Pearson's test: $p = 0.056$; $R = 0.15$) (Table 2). The age of the skid trail has a significant and negative correlation with litter and soil N, soil moisture, total porosity and pH, which indicates the increase of these properties after skidding operations.

In the studied skid trails, three types of humus from the five humus orders reported in the new European classification (EHGP) were identified (Figure 3a). Mull humus had the highest frequency and moder humus had the lowest frequency. The mull humus was observed in all three litter treatments, and its highest abundance was in the mixed beech litter treatment, while its lowest abundance was found in the pure beech litter treatment. Also, the amphi humus was observed in all three litter treatments, so its highest and lowest frequency was in pure beech and mixed beech litter treatments. The abundance of moder humus in the pure beech litter treatment was higher than in the beech-hornbeam litter treatment (Figure 3a).

The type of litter has a significant effect on the abundance of humus systems and humus forms (Figure 3b). Oligomull was the most common form of mull humus in all three litter treatments, and its highest frequency was observed in mixed beech litter treatment. Also, mesomull, eumull, and dysmull forms were observed in mixed beech litter and beech-hornbeam treatments. In all three litter treatments, eumacroamphi and eumesoamphi were the most common forms of amphi humus, and their highest frequency was observed in pure beech litter treatment. Leptoamphi and Pachyamphi were other forms of humus amphi which were present only in pure beech litter treatment. Hemimoder was the most common form of moder humus in the treatments, which along with eumoder was observed in the pure beech litter treatment (Figure 3b).



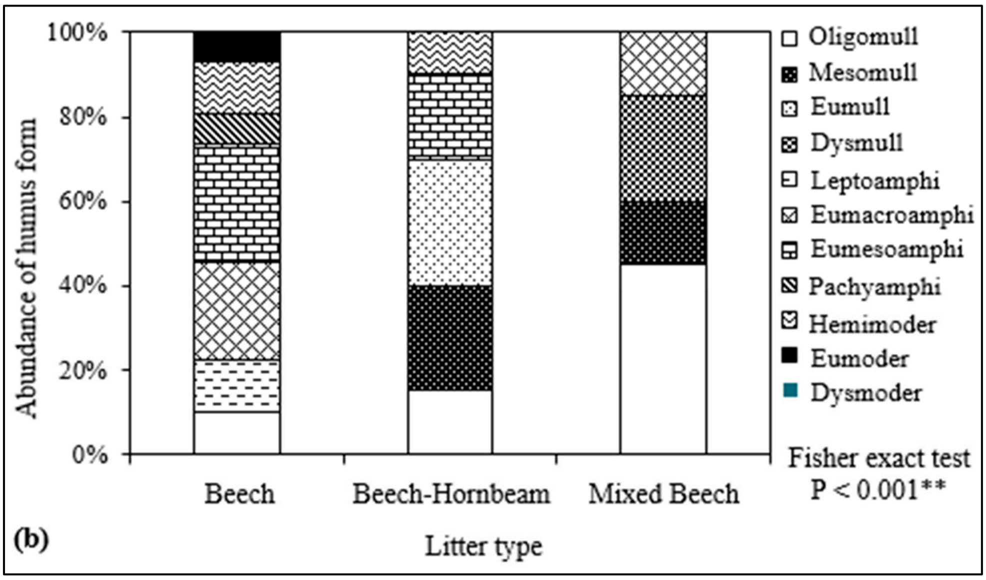


Figure 3. Abundance of humus systems (**a**) and humus forms (**b**) in relation to different Litter types.

The system (Figure 4a) and the humus form (Figure 4b) had a more uniform composition with an increase in the age of the skid trail. Three types of mull, amphi, and moder humus were observed in the 6-year skid trail, while mull and amphi humus were observed 20 years after the logging operations in the skid trail (Figure 4a). Oligomull was the most common form of mull humus in skid trails, and its highest abundance was observed in the 20-year-old skid trail. Mesomull, eumull, and Dysmull were other forms of mull humus that were observed in mixed beech and beech-hornbeam litter treatments. Eumesomphi was the most common form of amphi humus in the skid trails, and their highest frequency was observed 6 years after logging operations. Eumacroamphi and leptoamphi were among the other forms of amphi humus in all three skid trails. Hemimoder was observed as the most common form of moder humus in the 6 and 10-year skid trails, which were present along with eumoder and dysmoder in these routes (Figure 4b).

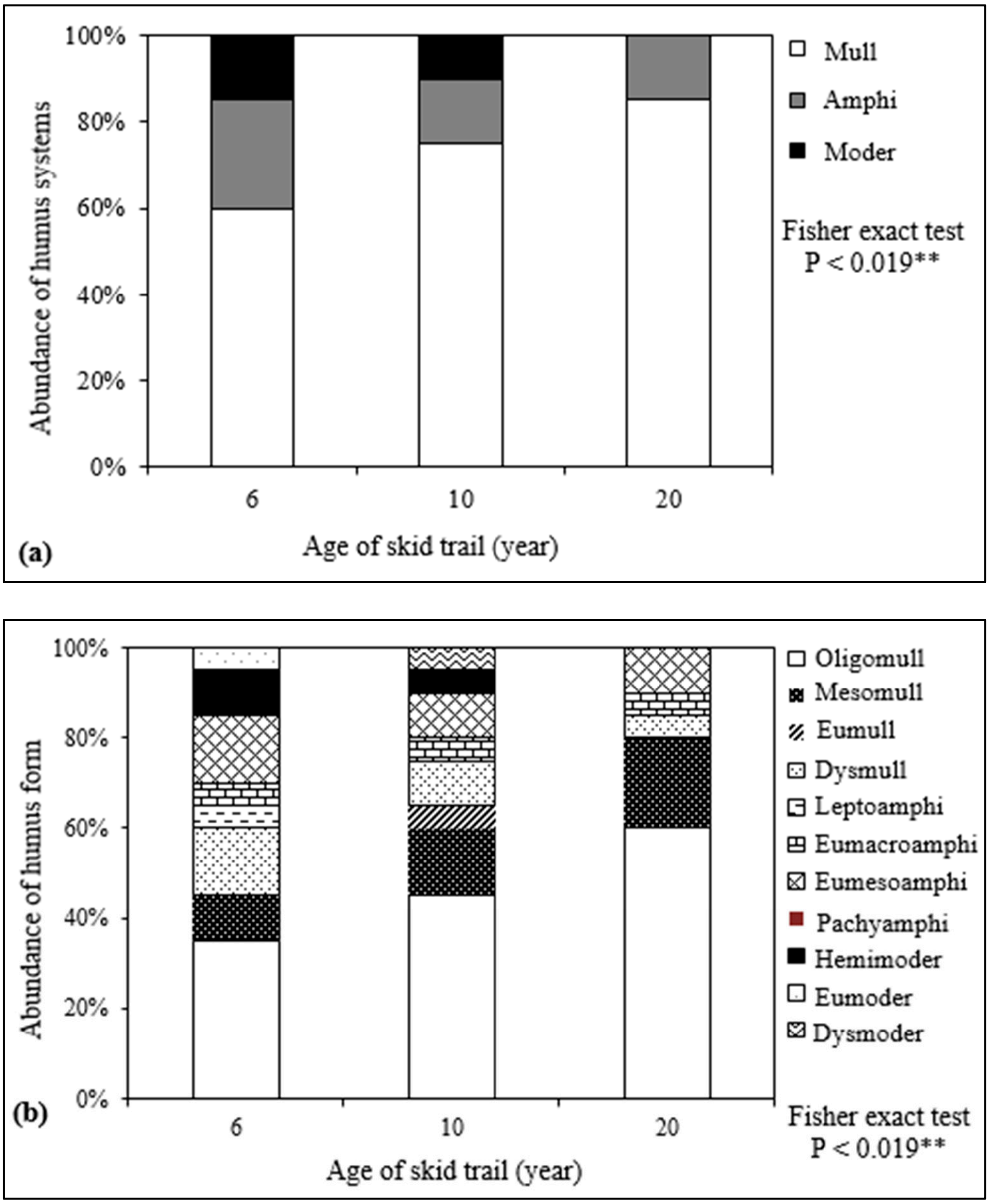


Figure 4. Abundance of humus systems (**a**) and humus forms (**b**) in relation to the age of the skid trail.

The average thickness of all organic horizons increased with the increase in the age of the skid trail after the logging operations, and this increase is greater in the 20-year-old skid trail and the beech litter treatment than in other conditions (Table 3). The average thickness of all organic horizons (OL, OF and OH) was higher in the beech litter treatment, and in this treatment, the organic litter (OL) had the highest thickness. On the contrary, in the mixed beech litter treatment, the thickness of organic horizons decreased, and the thickness of organic-mineral horizon (AH) increased. The Organic humus horizon (OH) was not observed in the mixed beech litter treatment, but the highest thickness of this layer belonged to the pure beech treatment, followed by the beech-hornbeam treatment in the 10-year skid trail (Table 3). The highest and lowest thickness of the organic-mineral horizon (AH) was found in the mixed beech litter treatment from the 20-year skid trail and the pure beech litter treatment from the 6-year skid trail, respectively.

The results of PCA analysis for treatments and dependent variables showed that the sum of the first and second axis explained 88.26% of the total variance (Figure 5). The thickness of OH and AH horizons, fractions of litter and soil physio-chemical properties (litter N, SM, TP, pH and soil N) were enhanced at sites with mixed beech litter (B-H-O), older skid trail (ST20) and undisturbed area (UND). The changes in litter and soil properties under mixed beech litter treatment and 20-year skid trail are related and positively correlated with mull humus form. In contrast, the thickness of the OL horizon, litter C, BD and soil C increased under the pure beech litter treatment and 3-year skid trail, which has a positive correlation with amphi and moder humus form (Figure 5).

Table 3. Thickness of organic humus (OL, OF and OH) and organic-mineral (AH) layers in relation to the interaction of different litter types and the age of skid trail. Different letters indicate a significant difference among different altitudes, done by Duncan's test ($p < 0.05$).

Age of Skid Trail (Year)	Litter Type (Forest Stands)	Humus Layers Thickness			
		OL (cm)	OF (cm)	OH (cm)	AH (cm)
6	Beech	4.4 ± 0.15^{ab}	1.8 ± 0.05^{a}	0.5 ± 0.00^{b}	1.4 ± 0.08^{b}
	Beech-Hornbeam	4.1 ± 0.15^{ab}	1.4 ± 0.05^{a}	-	1.8 ± 0.08^{b}
	Mixed Beech	3.4 ± 0.11^{b}	0.8 ± 0.03^{b}	-	2.2 ± 0.09^{b}
10	Beech	5.0 ± 0.15^{ab}	2.2 ± 0.05^{a}	1.0 ± 0.01^{a}	1.8 ± 0.08^{b}
	Beech-Hornbeam	4.1 ± 0.15^{b}	1.2 ± 0.05^{b}	0.8 ± 0.01^{a}	2.0 ± 0.08^{b}
	Mixed Beech	3.1 ± 0.15^{c}	1.0 ± 0.03^{b}	-	2.5 ± 0.09^{ab}
20	Beech	7.5 ± 0.27^{a}	2.0 ± 0.06^{a}	0.6 ± 0.00^{b}	2.2 ± 0.10^{b}
	Beech-Hornbeam	6.1 ± 0.27^{a}	1.5 ± 0.05^{a}	-	3.2 ± 0.17^{a}
	Mixed Beech	4.0 ± 0.18^{b}	0.8 ± 0.05^{b}	-	3.8 ± 0.17^{a}

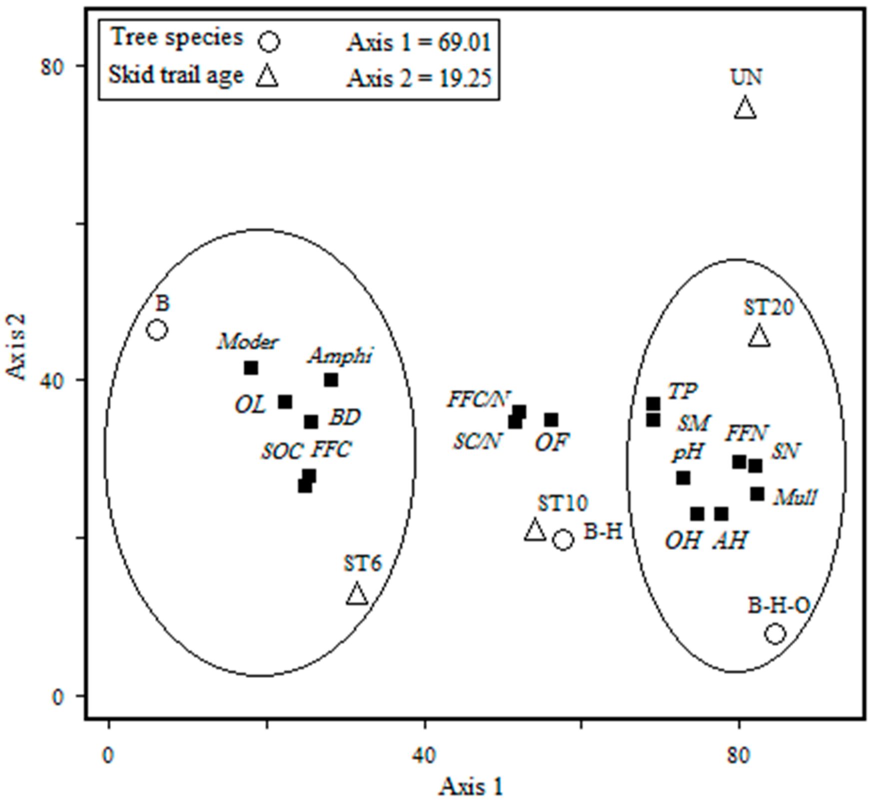


Figure 5. Principal component analysis (PCA) of the measured variables at various treatments; Litter type: B; Beech, B-H; Beech-Hornbeam, B-H-O; Mixed Beech; time since harvest: ST6; 6 years, ST10; 10 years, ST20; 20 years and UN: Undisturbed. Humus layers thickness (OL: Organic litter; OF: Organic fragmentation; OH: Organic humus and AH: Organic-mineral layer), Forest floor properties (FFC: Forest floor carbon; FFN: Forest floor nitrogen and FFC/N: Forest floor C/N), Soil physical properties (SM: Soil moisture; BD: Bulk density and TP: Total porosity) and Soil chemical properties (SOC: Soil organic carbon, SN: Soil nitrogen and SC/N: Soil C/N).

According to Pearson's correlation results, it was found that most of the examined characteristics under the influence of treatments have a significant correlation with each other (Figure 6). (Figure 6). The humus layers' thickness (OL, OF, OH and AH) has a significant and positive correlation with each other and with other characteristics of litter and soil (except bulk density). These layers have a significant and negative correlation with bulk density. The litter and soil C, unlike N, have a positive correlation with total porosity and a negative correlation with bulk density and soil pH (Figure 6).

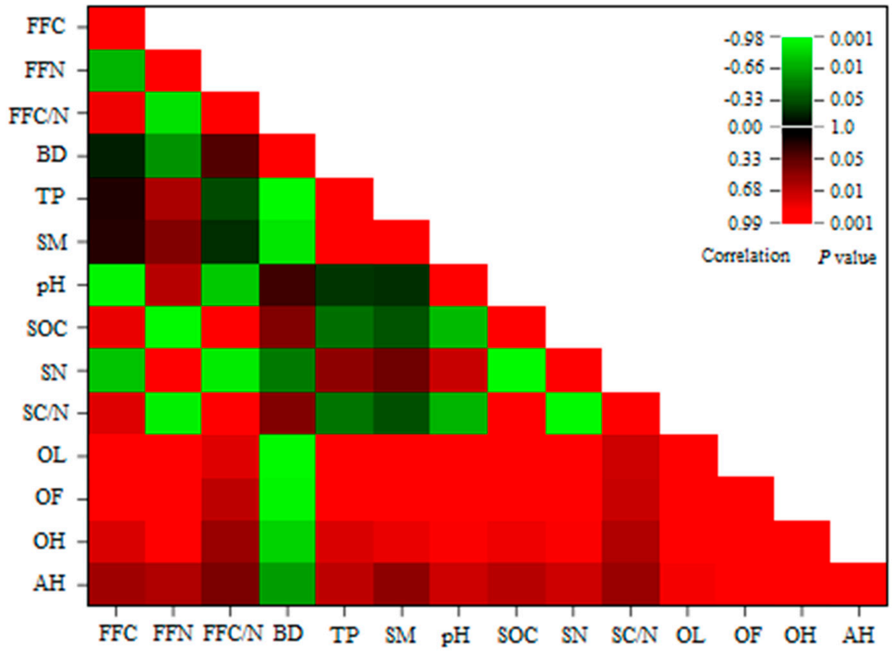


Figure 6. Pearson correlation coefficients (Heat map) of studied humus layers: thickness, forest floor, and soil properties.

4. Discussion

The combination of tree species and their productive litter, environmental factors (altitude above sea level, slope, temperature and humidity) and management actions lead to changes in humus forms [4,14]. Mull humus was the most common form under mixed beech litter, while amphi humus was the most common form under pure beech litter. Mull humus was the most common form under mixed beech litter, while amphi humus was the most common form under pure beech litter. The results of the study by Waez-Mousavi and Habashi [12] indicated the abundance of mull humus under the combination of tree species with favourable litter quality, which is consistent with the results of the present research. This is mainly the result of the high earthworm and bacterial activity, which creates a good mixture of organic matter and mineral particles in the crushed structure of topsoil. In agreement with the results of this study in a mixed forest, Ponge et al. [25] noted that mull systems are more abundant in favourable nutritional conditions and high diversity of tree species. In contrast, moder and amphi humus systems with OF and OH layers predominate in forest stands with low tree species and colder environments in areas of higher altitude [26,27]. Moder humus are abundant in the skid trail under pure beech litter with low soil pH, but the increase in amphi humus under pure beech litter is probably due to the high soil pH caused by the high concentration of calcium carbonate ($CaCO_3$) [28]. The concentration of $CaCO_3$ probably has a positive effect on the litter decomposition rate and soil microbial activity [28,29] and can probably facilitate the transition from moder to amphi state [30,31].

The abundance of the mull humus system increased with the age of the skid trail after the logging operation, while in the early years after the logging operation (6 years), humus systems had a more diverse form, and the percentage of mull abundance is higher than

Moder and Amphi. Six years after logging operations in the 6-year skid trail, disturbance and mixing of soil layers, reduction of surface litter, and changes in soil temperature and humidity, reduction in quality of the habitat of organisms and their activity led to the creation of an inappropriate mixture of organic materials and mineral particles in surface soil [1,32]. These changes may lead to a decrease in the abundance of mull humus and an increase in the moder and amphi humus in the early years after logging operations. With the increase in age of the skid trail and with the improvement of the litter and soil surface conditions of the logging roads with increasing thickness of the litter layer, improving the soil physical and chemical properties and the activity of soil organisms, the mull humus increased and the abundance of moder and amphi humus decreased.

According to the results, oligomull was the most abundant mull humus form under mixed beech litter, while Eumacroamphi, Eumesoamphi, and Hemimoder were the most common amphi and moder humus forms in the skid under pure beech litter. In line with these results, Bayranvand et al. [10] found that Oligomuil and Leptoamphi were more abundant in mixed beech forests, while Eumacroamphi, Eumesoamphi, and Pachyamphi were only observed in pure beech forests. In addition, De Nicola et al. [8] stated that mull, moder, and amphi humus are often visible in Mediterranean and mountain forests, while the identification of mor and tangel humus forms was not reported in these forests. The results of the study showed that the abundance of mull humus forms decreases from the skid trail under mixed beech litter to the skid with pure beech litter, while the abundance of amphi and moder humus forms increases. One of the reasons for the difference in the abundance of humus forms of the skid trails studied in this research is the presence of litter with different properties and as a result of the changes in the soil properties under the trees with different litters, which was also mentioned in the research of Bonifacio et al. [31]. Mixed beech forest stands usually have a higher quality in terms of forest floor (N content) and soil (i.e., pH, $CaCO_3$, soil N, soil C/N ratio, and nitrogen microbial biomass) than pure beech forests [10,33].

The average thickness of humus layers increased with the increase in the age of the skid trail and the improvement of the litter type quality from pure beech to mixed beech. Favourable conditions and sufficient time for organic matter decomposition in mixed forests (i.e., high temperature, optimal soil moisture, and high litter quality) are probably the cause [14,18,34]. In all skid trails, the thickness of all organic horizons (OL, OF and OH) under the influence of pure beech litter was higher as compared to other treatments, while the average thickness of the organic-mineral horizon was increasing under mixed beech litter. This may be related to a decrease in pH under the influence of pure beech litter and a higher litter decomposition rate of mixed beech stand [35,36]. The amount of organic carbon in the humus layers is an important reason for the accumulation and increase in litter thickness in amphi humus under pure beech litter compared to the mull with a low thickness of organic matter under high-quality mixed beech litter [4,17,33]. In this regard, Zanella et al. [6] stated that the C/N ratio in the organic layers of mull humus was lower than the amphi layers, so the C/N ratio is a very important indicator to show the speed of decomposition in different forms of humus. In addition, the low C/N ratio in the soil under mull humus can indicate the low C/N ratio in the litter of tree species [6,13].

In this study, the highest thickness of the organic humus (OH) was observed in all skid trails under the influence of pure beech litter. Changes in the organic layer thickness can be attributed to a reduction in the quality of pure beech litter and higher soil moisture [4,6,37], which reduces mineralization rates [25,26]. To determine the distribution pattern of humus forms, the presence or absence of the H horizon has been mentioned as the most important variable [10,38]. Also, Zanella et al. [6] in the classification of humus form considered the absence of the H horizon as the determinant of mull humus and the thickness of this horizon as one of the most important factors for determining amphi and moder humus.

5. Conclusions

In this study, the forms of ground humus in compacted skid trails were investigated in different years after logging operations. For this purpose, two factors of different tree litter and skid trail age were evaluated as indicators of the variability of humus types. Mull humus is dominant under the influence of mixed beech litter with high quality, while in pure beech litter Amphi humus was the most abundant form of humus. All three types of humus, mull, moder, and amphi were observed on the skid trail with beech-hornbeam litter. According to the results, oligomull was the most abundant mull humus form under mixed beech litter, while Eumacroamphi, Eumesoamphi, and Hemimoder were the most common amphi and moder humus forms in the skid under pure beech litter. In all skid trails, the thickness of organic horizons under pure beech litter was higher compared to other treatments, while the average thickness of organic-mineral horizon was increasing under mixed beech litter. The humus layers' thickness (OL, OF, OH and AH) has a significant and positive correlation with each other and with other characteristics of litter and soil, except bulk density. The results of this study help researchers to better understand the effective ecological factors in improving the condition of degraded soils. To manage forest soils and accelerate soil recovery time after forest operations, it is possible to evaluate soil ecological factors such as humus and soil fertility by determining suitable tree species in a mixed forest stand. Finally, extensive and practical studies on humus forms and their relationship with other ecosystem components can introduce a suitable model for soil fertility enhancement.

Author Contributions: Conceptualization, H.S., M.J. and R.P.; methodology, H.S., M.J., R.V. and R.P.; validation, H.S., M.J. and R.P.; formal analysis, H.S., M.J. and R.P.; investigation, H.S. and M.J.; data curation, H.S., M.J., R.V. and R.P.; writing—original draft preparation, H.S. and M.J.; writing—review and editing, H.S., M.J., R.V. and R.P.; supervision, H.S., M.J. and R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

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