sustainability

MDPI

Article

The Influence of Slope Positions on the Recovery Response of Compacted Soil Properties and Enzyme Activity in an Oriental Beech Stand in the Hyrcanian Forests, Iran

Meghdad Jourgholami [1], Alireza Ramineh [1], Ghavamodin Zahedi Amiri [1] and Eric R. Labelle [2,*]

[1] Faculty of Natural Resources, Department of Forestry and Forest Economics, University of Tehran, Karaj 999067, Alborz, Iran; mjgholami@ut.ac.ir (M.J.); alirezaramineh@ut.ac.ir (A.R.); ghavamza@ut.ac.ir (G.Z.A.)
[2] Department of Ecology and Ecosystem Management, Technische Universität München, Hans-Carl-von-Carlowitz-Platz 2, D-85354 Freising, Germany
* Correspondence: eric.labelle@tum.de; Tel.: +49-(0)816-171-4760

Received: 9 March 2019; Accepted: 29 March 2019; Published: 2 April 2019

check for updates

Abstract: Several studies emphasize the effects of slope position on divergences of soil properties in forest ecosystems, but limited data is available on the impact of slope position on recovery levels of soil, which were exposed to compaction due to machine traffic. This study examined the effects of slope position (i.e., S; summit, BS; backslope, and TS; toeslope) on recovery rate of soil properties and enzyme activity four years after ground-based harvesting operations were performed on machine operating trails, compared to the undisturbed areas (UND) in the Hyrcanian forests (north of Iran). Soil properties and enzyme activity of compacted soil in machine operating trails showed significant trend differences among the slope positions. A significantly lower soil bulk density, penetration resistance, soil moisture, aggregate stability, pH, sand, and C/N ratio were found in TS compared to the values recorded in the BS and S treatments. Conversely, total porosity, macroporosity, silt, clay, organic C, total N, available nutrients (i.e., P, K^+, Ca^{2+}, and Mg^{2+}), fulvic and humic acid, earthworm density and dry mass as well as fine root biomass were higher in TS than in the BS and S treatments. Soil microbial respiration, MBC, NH_4^+, NO_3^-, N mineralization, and MBN were significantly higher in the UND areas followed by TS > BS > S treatment. The highest activity levels of enzymes (i.e., urease, acid phosphatase, arylsulfatase, invertase, and ß-N-acetylglucosaminidase) were detected in the UND areas, followed by TS > BS > S treatment. The highest recovery levels of all soil properties and enzyme activity were found in TS, followed by BS > S treatment. However, the full recovery of soil properties did not occur even after a 4-year period, compared to the UND areas. Our study results highlight the significance of the slope position in augmenting divergence in soil properties and enzyme activity after ground-based machine traffic.

Keywords: soil compaction; soil integrity; machine operating trail; mechanized harvesting; sustainable forest management

1. Introduction

Catena slope positions in the forest ecosystems play a crucial role in creating micro-environments and soil heterogeneity [1], which result in particular ecological and biological processes of soil, and lead to miscellaneous nutrient cycling, composition/structure of the microbial population, as well as enzyme activity [2,3]. The hydrological processes and soil formation stages are regulated by topographic indices [4,5]. Different landscape positions within a slope profile have significant effects on soil properties [6,7]. Variations in topographic characteristics such as elevation, slope gradient, and slope aspect lead to immense changes in climatic and soil factors that contribute to the soil organic carbon (SOC) variability [1,7,8]. In general, soil physical, chemical, and biological indices, as well as enzyme activity are affected by parent material, vegetation, climate, and topographic conditions [3,7,9]. Generally, the slope position and the slope aspect regulate the hydrological processes and the level of solar radiation reaching the ground, which, in turn, introduces microclimates in smaller area [7,8].

Topographic features such as slope gradient, shape (convex or concave), position (the summit, shoulder, backslope, footslope, and toeslope), and streams are key factors that influence the development and variability in soil properties, nutrient cycling, decomposition rate of organic matter, and soil-air gas exchange [1,5,8]. In the Hyrcanian forests located in northern Iran, soil water content, SOC, and total nitrogen as well as soil microbial respiration were significantly affected by the catena shape and slope position [9]. In the Van Lake Basin, Turkey, Karaca et al. [1] revealed that the various topographic locations also significantly influenced soil properties including soil texture, electrical conductivity (EC), pH, lime, organic matter, and nutrient content as a result of materials being leached, transported, and accumulated. Topography can influence soil formation and development in three ways: through the water uptake and retention in the soil, loss of soil nutrients by erosion, and transporting suspended and water-soluble materials from one point to another [3,6,7]. Zhu et al. [7] concluded that SOC is highly affected by elevation and slope position in grassland regions. In addition, Lozano-García and Parras-Alcantára [3] reported that SOC and N content significantly increased by moving from the summit to toeslope positions.

Forest soils are an important habitat within the forest ecosystems. In their natural state, they often present specific conditions such as significant organic matter [10], low soil bulk density, and high porosity [11], making forest soils sensitive to mechanical forces and soil compaction [12–14]. The mechanical stress applied by ground-based machines used during timber harvesting operations can increase soil bulk density [15–17], condense soil pores [12], impair soil aggregates [18], and cause soil displacement [19,20]. Additionally, ground vegetation and litter layer (i.e., L, F, and H layers) can be destroyed or significantly disturbed following ground-based skidding, thus leaving the bare mineral soil exposed to raindrop impacts, which can result in increased runoff flow and sediment yield [10]. Soil compaction can also have negative effects on abiotic and biotic components in forest soils where detrimental impacts on microbe population have been reported [20,21], which ultimately had considerable influence on nutrient cycling [13,17].

Forest soil enzymes play a key role in soil processes such as the nutrient cycling and energy conversion through chemical, physical, and biological reactions [22]. The response of soil enzymes to changes caused by forest management activities can be more rapid than with other soil properties [22]; hence, many authors suggest that the soil extracellular enzymes can be used as indicators for soil fertility, health, and biological change [23–25]. Significant positive correlations were found among soil microbial populations and extracellular enzyme activity; because the organic matter decomposition and nutrient cycling occurred through micro-organism activity [26]. Therefore, soil microbial biomass can be used as a sensitive indicator to soil ecological sustainability [22,26]. As previously reported by Dick et al. [23], increasing soil bulk density through machine traffic on forest soils can lead to significantly decreased soil enzyme activity (i.e., dehydrogenase, phosphatase, arylsulfatase, and amidase) as compared to an undisturbed soil.

The remediation and reclamation of compacted forest soils can be achieved by accelerating the soil physical and biological features with some artificial measures such as earthworms inoculation [18], seedling plantation [27,28], and mulching [10]. Natural processes such as the root-soil interactions, the expansion—retraction of clay particles, the freezing—thawing of water in soil, and the activities of soil biota can also support, to a certain degree, the natural restoration of compacted soil properties [21,29]. However, natural recovery of compacted forest soils is a long-term mechanism, which may occur over a few years to several decades [18,28].

The Hyrcanian deciduous temperate forests are known as unique ecosystems in the northern hemisphere because they encompass a diverse range of macro- and micro-topographies. Several studies highlight the effects of topography and slope position on divergences of soil properties in forest ecosystems, but no data is currently available on the impact of slope position on recovery levels of soils, which were exposed to machine-induced compaction through harvesting operations performed in forest stands. This study aimed to elucidate the effects of slope positions on recovery levels of compacted soil properties and enzyme activity within four years after machine operations performed on machine operating trails, compared to undisturbed or control (UND) areas. We tested the hypothesis that slope position may affect the recovery process of soil physical, chemical, and biological properties, as well as enzyme activity.

2. Materials and Methods

2.1. Site Description

The study site is an old-growth oriental beech stand in the Kheyrud forest of the Hyrcanian forests (40°46′ N, 55°49′ E). The investigated site has a slope ranging from 1–40% facing north and an elevation in the range of 1170–1220 m above sea level. The mean annual rainfall is 1420 mm with the highest precipitation occurring in October and the lowest in July [14]. The climate of the investigated area is humid cold with a one-month dry period in July. Mean annual temperature is 7.9 °C with the hottest and coldest months in July and January, respectively. The soils are Alfisols with clay loam texture (according to the USDA Soil Taxonomy) from limestone; belonging to the upper Jurassic and lower Cretaceous periods. Forest stands are composed of beech (*Fagus orientalis* Lipsky) and are accompanied with other species including hornbeam (*Carpinus betulus* L.), velvet maple (*Acer velutinum*), and Caucasian alder (*Alnus subcordata* C.A.M.). The main herbaceous species of the ground vegetation are *Cyclamen coum* Mill., *Prunella vulgaris* Huds. *Rhynchocorys maxima* Rieht., *Galium odoratum* L., *Mercurialis perennis* L., *Oplismenus undulatifolius* Ard., *Euphorbia amygdaloides* L., and *Viola sieheana* Becker. Semi-mechanized forest operations were performed by chainsaw in March 2014 where trees were felled, delimbed and bucked to size. The processed logs were then extracted by a Timberjack 450C wheeled skidder in August 2014. The four-wheel drive skidder had an empty weight of 10.3 metric tons (tire inflation pressure set to 220 kPa) and the average load volume was 2.9 cubic meters. All traffic was performed on machine operating trails of 3.5 m in width.

2.2. Experimental Design

To study the effects of catena position on recovery values of compacted soil, four machine operating trails were selected four years after skidding operations were completed (2014) (Figure 1a–c). More specifically, three catena positions were selected in each machine operating trail including the summit (S), backslope (BS), and toeslope (TS) as well as the undisturbed or control areas (UND) as treatments. Sampling plots were established in different trail segments exposed to a high level of machine traffic (> 15 machine cycles; a machine cycle consisted of one unloaded and one loaded pass with the skidder). In each catena position, three plots were randomly established and a plot (with length of 20 m and width of 4 m) was randomly selected for soil sampling in August 2018. In each selected sample plot, five transects were set up perpendicular to the longitudinal axis of the trail with a spacing of 4 m between transects (Figure 1b,c). Three of the five transects were randomly selected for soil sampling [17]. In each sample plot (Figure 1c), nine soil samples (six samples in tracked locations and three samples from between tracks) were collected from the machine operating trails and three soil samples were collected in the undisturbed or control areas. The undisturbed or control areas (UND area) were established at a distance of 20 m from the machine operating trails in each plot (Figure 1b,c). In total, 144 soil samples (i.e., 4 machine operating trails × 3 slope positions × 12 samples in each plot (nine samples in the compacted area + three samples in the control area)) were collected and analyzed in August 2018.

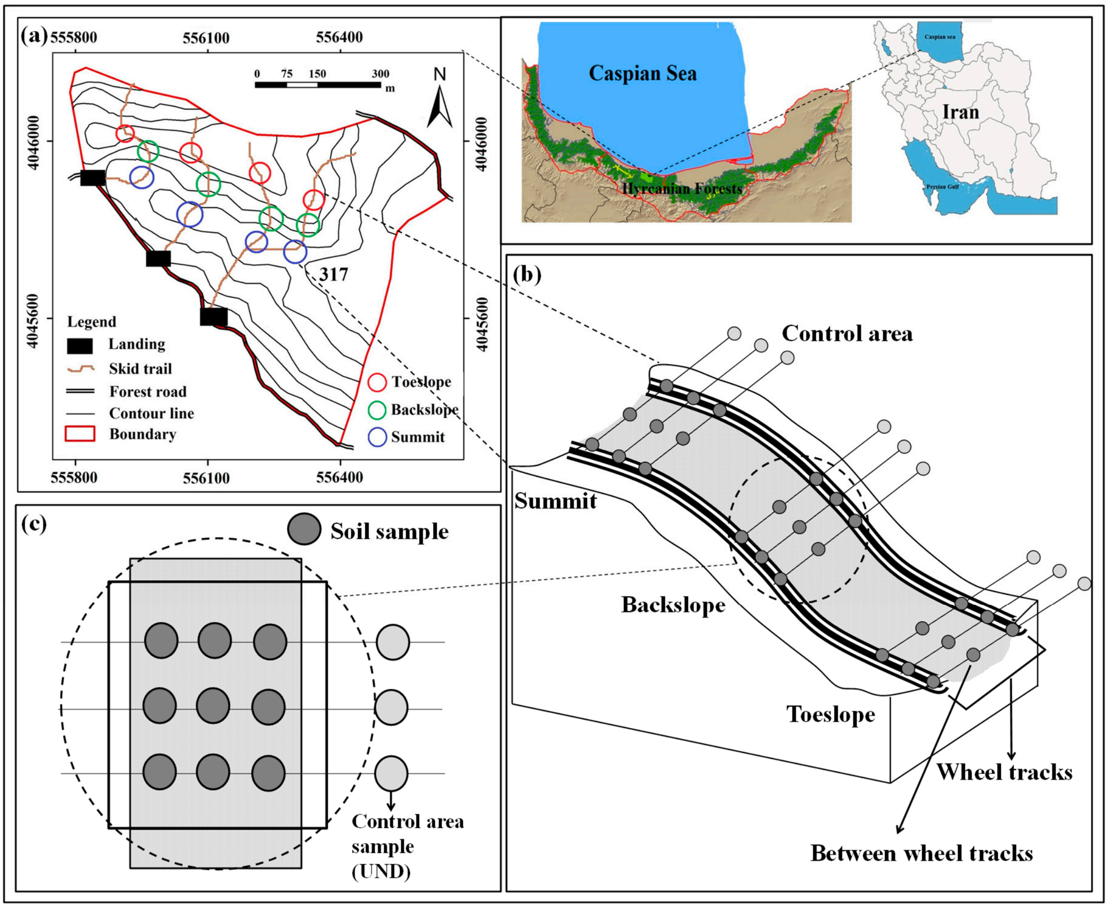

Figure 1. The study area in Kheyrud forests in the Hyrcanian forests (40°46′ N, 55°49′ E) and the schematic of the experimental design on the machine operating trail (**a**). The treatments are included as follow: the undisturbed or control areas (UND), toeslope (TS), backslope (BS), and summit (S) (**b**); soil sampling point on the machine operating trails (**c**).

2.3. Data Collection and Laboratory Analysis

A steel cylinder (length of 40 mm and diameter of 56 mm) was used to collect soil samples from the surface soil of 0–10 cm. Following the extraction, soil samples were placed in plastic bags, sealed, labeled, and transported to the lab for further analysis. Soil samples were weighted after collection and then oven-dried at 105 °C until reaching a constant mass to determine the water content and the soil bulk density (ds). The hydrometer method was used to determine the soil particle size distribution for particles smaller than 0.075 mm [30], and the larger particles by sieving through a series of sieves of varying apertures. The water desorption method was applied to determine the macroporosity [31]. The soil penetration resistance (PR) was measured using an analog hand-held soil penetrometer (Eijkelkamp 06.01.SA penetrometer with a 60° cone and a 1 m maximum measuring depth). The wet sieving procedure was used to determine the aggregate stability [32]. To assess the soil particle density (dp), the ASTM D854-00 2000 standard was applied and the formula as (Total porosity (TP) = [1 − (soil bulk density (ds)/ soil particle density (dp))] × 100) was used to determine total porosity (TP).

To analyze the biological properties, approx. 2 kg of soil was also collected from each sampling point, transported to the lab, and stored in plastic bags at 4 °C. Soil pH with a ratio of soil to water of 1:2.5 was measured using the Orion Ionalyzer (Model 901) pH meter. EC was measured by an Orion Ionalyzer EC meter with a ratio of soil to water of 1:2.5 solution. Soil organic C was determined by applying the Walkley–Black technique [33] and total N by using the Kjeldahl method [34]. The available phosphorous (P) was determined using the Olsen method with a spectrophotometer, and available potassium (K), calcium (Ca), and magnesium (Mg) (by ammonium acetate extraction at pH 9) by applying an atomic absorption spectrophotometer [35]. The earthworm sampling and counting was manually done at the surface soil with area of 25 × 25 cm and 0–10 cm depth after removing the litter layer. After collection, the earthworms were washed, weighed, and oven-dried at 60 °C for 24 h to determine the earthworm dry mass [17]. To measure fine root biomass, fine roots (<2 mm in diameter) were extracted from each sample and dried at 70 °C to a constant mass [35]. By measuring the CO_2 evolved in a 3-day incubation experiment at 25 °C, soil microbial respiration was measured [35]. The chloroform fumigation–extraction method was also used to determine the microbial biomass carbon (MBC) and nitrogen (MBN) in the soils [34]. Soil NH_4^+ and NO_3^- were extracted with 2 M KCl solution (with a ratio of soil to solution of 1:5) and determined using the colorimetric techniques [25]. N mineralization was determined by aerobic incubation of the soils [36]. Urease activity (EC 3.5.1.5) was analyzed using 200 µmol urea as substrate, incubated for 2 h at 37 °C. The acid phosphatase activity was determined in a MUB buffer (pH 6.5), incubated for 1 h at 37 °C [25]. A p-Nitrophenyl sulphate was used for incubation for 1 h at 37 °C to analyze the arylsulphatase activity (EC 3.1.6.1). To detect invertase (EC 3.2.1.26), 1.2% sucrose solution was used for incubation at 3 h at 50 °C [37]. The ß-N-acetyl-glucosaminidase (EC 3.2.1.30) was analyzed in 100 µmol acetate buffer at pH 5.5 [25].

2.4. Statistical Analyses

A factorial experiment with a complete block design was randomly assigned to the treatments (TS, BS, S, and UND). Generalized linear modeling (GLM) was used to relate the recovery of soil properties and enzyme activity to treatment. To compare soil properties among different slope positions, one-way analysis of variance (ANOVA) was used. The normality and homogeneity of variance were verified with the Kolmogorov–Smirnov and the Levene tests (α = 0.05). The post hoc test was used to verify the statistically significant differences between the treatments by the Tukey test at $P \leq 0.05$. The relationships between soil physical, chemical, and biochemical as well as biological properties with soil enzyme activity in four treatments were determined using the Pearson correlation. All statistical tests were performed using the SPSS software package (release 17.0; SPSS, Chicago, IL, USA).

3. Results

3.1. Soil Physical, Chemical, and Biological Properties

Results showed that all the soil physical, chemical, and biological properties tested (with the exception of EC) were influenced by the treatments ($p < 0.001$). Because the soil properties originating from the different UND areas were similar without any statistical differences, these data were grouped and reported as mean values. Average soil bulk density and penetration resistance were lower in the UND areas and TS position as compared to the other positions (Table 1). More specifically, average soil bulk density was 33% higher in the S position as compared to the UND areas whereas penetration resistance was 80% higher in the S position as compared to the UND areas. Total porosity and macroporosity, soil moisture, aggregate stability, and silt were significantly higher in the UND areas and TS position than the amounts recorded at the BS and S positions. Additionally, soil moisture and aggregate stability were 50% and 40% lower in the S position as compared to the UND areas, respectively. The highest sand content was measured in the S and BS positions. The highest recovery values of all soil physical properties tested were detected in the TS position, followed by values at the BS and S positions, compared to the UND areas.

Concerning chemical properties, there were no significant differences in EC among slope positions and UND areas. Soil pH was significantly higher in S positions than in BS, TS and the UND areas. Also, soil C/N ratios were significantly lower in S positions than in BS, TS and the UND areas. Soil organic C, N, available nutrients (i.e., P, K, Ca, and Mg), fulvic acid, and humic acid were also highest in the UND areas followed by TS and lowest in the BS and S positions. Likewise, average soil pH and

C/N ratio were 24% and 44% higher in the S position as compared to the UND areas, whereas SOC and N were 3.7 and 5.1 times lower in the S position as compared to the UND areas, respectively.

Significantly higher values of earthworm density and dry mass were measured in the UND areas followed by TS > BS > S treatment. Fine root biomass showed no significant difference between the UND areas and TS. Furthermore, earthworm density was 6.4 times lower in the S position as compared to the UND areas, whereas fine root biomass was 45% lower in the S position than the UND areas.

Table 1. Mean (±std; n = 144) of soil physical, chemical, and biological properties in the four treatments. The treatments are included as follow: the undisturbed or control areas (UND), toeslope (TS), backslope (BS), and summit (S).

Soil Properties		Control and Slope Positions				*F* Test	*p* Value
		UND	TS	BS	S		
Physical properties	Bulk density (g cm^{-3})	0.97 ± 0.07c	1.08 ± 0.08b	1.25 ± 0.10a	1.29 ± 0.10a	98.24	<0.001
	Total porosity (%)	62.69 ± 2.83a	58.46 ± 3.16b	51.92 ± 4.04c	50.39 ± 3.75c	98.24	<0.001
	Macroporosity (%)	36.98 ± 3.52a	32.74 ± 3.52b	26.48 ± 3.23c	21.66 ± 3.34d	141.93	<0.001
	Penetration resistance (MPa)	0.96 ± 0.10d	1.14 ± 0.11c	1.47 ± 0.22b	1.73 ± 0.20a	152.72	<0.001
	Soil moisture (%)	42.61 ± 6.17a	36.51 ± 6.37b	27.93 ± 4.91c	21.47 ± 5.30d	95.48	<0.001
	Aggregate stability (%)	65.71 ± 6.27a	58.12 ± 6.88b	47.83 ± 6.39c	39.18 ± 7.17d	108.7	<0.001
	Sand (%)	23.49 ± 0.81d	26.49 ± 0.73c	28.77 ± 0.47b	31.50 ± 1.29a	544.62	<0.001
	Silt (%)	43.09 ± 1.14a	40.18 ± 1.14b	38.89 ± 1.14c	36.11 ± 1.11d	439.33	<0.001
	Clay (%)	33.42 ± 1.56a	33.33 ± 1.08a	32.34 ± 1.21a	32.39 ± 2.18a	9.0	<0.001
Chemical properties	pH (1:2.5 H_2O)	5.64 ± 0.56d	6.02 ± 0.31c	6.57 ± 0.29b	6.98 ± 0.51a	67.16	<0.001
	Electrical conductivity (EC) (ds m^{-1})	0.23 ± 0.03a	0.22 ± 0.05a	0.23 ± 0.03a	0.24 ± 0.03a	1.93	0.13
	SOC (%)	7.26 ± 1.38a	4.01 ± 1.52b	2.78 ± 0.73c	1.95 ± 0.63d	152.61	<0.001
	N (%)	0.61 ± 0.10a	0.29 ± 0.07b	0.18 ± 0.07c	0.12 ± 0.05d	311.92	<0.001
	C/N ratio	11.88 ± 0.80c	13.5 ± 3.10b	16.25 ± 2.64a	17.16 ± 2.29a	38.22	<0.001
	Available P (mg kg^{-1})	25.45 ± 4.42a	21.27 ± 3.02b	17.14 ± 2.35c	15.39 ± 1.96c	76.47	<0.001
	Available K^+ (mg kg^{-1})	193.87 ± 23.77a	179.31 ± 22.43b	152.47 ± 19.39c	137.08 ± 13.54d	58.19	<0.001
	Available Ca^{2+} (mg kg^{-1})	167.24 ± 20.23a	152.75 ± 11.97b	129.73 ± 16.73c	107.61 ± 11.63d	102.02	<0.001
	Available Mg^{2+} (mg kg^{-1})	49.31 ± 5.41a	43.17 ± 4.08b	36.04 ± 3.8c	31.28 ± 4.36d	114.03	<0.001
	Fulvic acid (mg/100 g)	380.12 ± 37.89a	310.81 ± 36.72b	205.43 ± 47.22c	128.37 ± 36.04d	283.24	<0.001
	Humic acid (mg/100 g)	185.27 ± 37.48a	151.03 ± 35.53b	98.74 ± 32.96c	71.29 ± 18.63d	92.18	<0.001
Biological properties	Earthworm density (n m^{-2})	2.05 ± 0.34a	1.65 ± 0.27b	0.75 ± 0.25c	0.32 ± 0.13d	337.23	<0.001
	Earthworm dry mass (mg m^{-2})	27.08 ± 6.72a	22.46 ± 5.44b	11.04 ± 3.91c	4.17 ± 2.80d	161.44	<0.001
	Fine root biomass (g m^{-2})	86.13 ± 15.64a	78.67 ± 14.7a	62.34 ± 12.59b	47.09 ± 7.44c	64.79	<0.001

Note: ds: soil bulk density; SOC: soil organic carbon. Note: Results of the ANOVAs (F test and *p* value) are given. Different letters after means within each treatment indicate significant differences by Tukey test ($p < 0.05$).

3.2. Soil Microbial Properties and Enzyme Activity

Soil microbial properties and enzyme activity significantly differed among treatments and the UND areas (Table 2; $p < 0.001$). Soil microbial respiration, MBC, N mineralization, and MBN were significantly higher in the UND areas followed by TS > BS > S treatment (Table 2). However, NH_4^+ and NO_3^- did not show any significant differences between the UND areas and TS, but were significantly higher in the UND areas and TS than in the BS and S treatments. Moreover, soil microbial respiration, MBC, and MBN were 55, 77, and 65% lower in the S position as compared to the UND areas, respectively. The highest activity levels of urease, acid phosphatase, arylsulfatase, invertase, and ß-N-acetylglucosaminidase were found in the UND areas, followed by TS > BS > S treatment. Significant positive correlations ($p < 0.05$) were reported among enzyme activities, soil moisture content, SOC, N, available P and K, fulvic acid, humic acid, earthworm dry mass, soil microbial respiration, fine root biomass, MBC, NH_4^+, NO_3^-, N mineralization, and MBN (Table 3). Soil bulk density, pH, and C/N ratio had significant negative correlations ($p < 0.05$) with enzyme activities.

The highest recovery value of all soil physical, chemical, biological, and microbial properties as well as enzyme activity were detected in the TS treatment followed by BS > S treatment, compared to UND areas. However, full recovery of the soil properties and enzyme activity, as compared to those recorded at the UND areas, did not occur among treatments (i.e., TS, BS, and S) within a 4-year period after machine traffic (Tables 1 and 2).

Table 2. Mean (±std; n = 144) of soil microbial and enzyme activity in the four treatments. The treatments are included as follow: the undisturbed or control areas (UND), toeslope (TS), backslope (BS), and summit (S).

Soil Properties		Control and Slope Positions				*F* Test	*p* Value
		UND	TS	BS	S		
C and N Microbial properties	SMR	0.51 ± 0.13a	0.45 ± 0.09b	0.33 ± 0.07c	0.23 ± 0.07d	65.53	<0.001
	MBC	572.03 ± 105.03a	485.81 ± 52.13b	241.76 ± 55.72c	134.28 ± 53.73d	305.68	<0.001
	NH_4^+	22.14 ± 5.27a	19.32 ± 6.65a	11.81 ± 4.72b	7.05 ± 3.02c	66.39	<0.001
	NO_3^-	21.84 ± 6.19a	19.32 ± 4.91a	10.06 ± 4.42b	6.11 ± 2.49c	90.97	<0.001
	N Min	34.61 ± 8.67a	29.04 ± 8.40b	19.48 ± 5.99c	12.43 ± 4.28d	70.17	<0.001
	MBN	38.15 ± 7.68a	33.61 ± 7.53b	18.93 ± 6.28c	13.27 ± 4.27d	115.63	<0.001
Enzyme activity	Urease	22.89 ± 3.76a	19.51 ± 3.84b	11.41 ± 3.39c	6.59 ± 2.39d	172.94	<0.001
	APH	327.08 ± 45.68a	294.55 ± 46.98b	194.85 ± 37.30c	132.61 ± 26.51d	181.09	<0.001
	Arylsulfatase	186.04 ± 32.99a	153.35 ± 33.43b	92.28 ± 25.06c	65.47 ± 20.77d	134.41	<0.001
	Invertase	237.41 ± 36.52a	204.38 ± 34.49b	123.64 ± 32.17c	84.03 ± 25.26d	171.95	<0.001
	NAG	176.05 ± 23.8a	153.76 ± 19.57b	98.41 ± 18.24c	69.27 ± 12.98d	239.73	<0.001

Note: Results of the ANOVAs (F test and *p* value) are given. Different letters after means within each treatment indicate significant differences by Tukey test ($p < 0.05$). C and N microbial properties; SMR: soil microbial respiration (mg CO_2-C g $soil^{-1}$ day^{-1}); MBC: microbial biomass carbon (mg kg^{-1}); NH_4^+: ammonium (mg kg^{-1}); NO_3^-: nitrate (mg kg^{-1}); N Min: nitrogen mineralization (mg N kg $soil^{-1}$); MBN: microbial biomass nitrogen (mg kg^{-1}). Enzyme activity; urease (µg NH_4^+–Ng^{-1} 2 h^{-1}); APH: acid phosphatase (µg PNP g^{-1} h^{-1}); arylsulfatase (µg PNP g^{-1} h^{1}); invertase (µg Glucose g^{-1} 3 h^{-1}); NAG: ß-N-acetylglucosaminidase (µg g^{-1} h^{-1}).

Table 3. Pearson correlation between soil physical, chemical, biochemical, and biological properties with soil enzyme activity in four treatments.

Soil Properties	Bulk Density	Soil Moisture	pH	SOC	N	C/N Ratio	Available P	Available K	Fulvic Acid
Urease	−0.68 **	0.62 *	−0.53 *	0.64 *	0.70 **	−0.55 **	0.70 **	0.73 **	0.77 **
Acid phosphatase	−0.93 **	0.88 **	−0.73 **	0.86 **	0.84 **	−0.51 *	0.92 **	0.60 *	0.94 **
Arylsulfatase	−0.68 **	0.60 *	−0.51 *	0.64 **	0.71 **	−0.54 **	0.70 **	0.70 **	0.74 **
Invertase	−0.59 *	0.72 **	−0.73 **	0.71 **	0.71 **	−0.49 *	0.56 *	0.72 **	0.78 **
NAG	−0.73 **	0.67 **	−0.57 **	0.68 **	0.74 **	−0.57 **	0.75 **	0.72 **	0.80 **
Soil Properties	**Humic Acid**	**Earthworm Density**	**Soil Microbial Respiration**	**Fine Root Biomass**	**Microbial Biomass Carbon**	NH_4^+	NO_3^-	**Nitrogen Mineralization**	**Microbial Biomass Nitrogen**
Urease	0.68 **	0.98 **	0.74 **	0.64 **	0.86 **	0.74 **	0.63 **	0.61 *	0.83 **
Acid phosphatase	0.96 **	0.82 **	0.48 *	0.95 **	0.88 **	0.84 **	0.68 **	0.89 **	0.87 **
Arylsulfatase	0.67 **	0.97 **	0.71 **	0.62 *	0.84 **	0.73 **	0.58 **	0.59 *	0.81 **
Invertase	0.62 *	0.75 *	0.73 **	0.56 *	0.84 **	0.72 **	0.92 **	0.65 **	0.76 **
NAG	0.73 **	0.99 **	0.73 **	0.68 **	0.89 **	0.77 **	0.66 **	0.66 **	0.85 **

Note: SOC: soil organic carbon; NAG: ß-N-acetylglucosaminidase (µg g^{-1} h^{-1}). * $p < 0.05$; ** $p < 0.01$.

4. Discussion

4.1. Soil Physical, Chemical, and Biological Properties

The current study demonstrated that soil physical, chemical, and biological properties were influenced by topography and more specifically slope positions within the area trafficked by ground-based machines. Particularly, soil moisture and organic matter content were regulated by topography and slope positions, which is in line with [4,7,9]. Because water is directly involved in chemical and biological activities of decomposition and degradation as well as in physical degradation, changes of soil moisture directly affected the evolution of soil profiles and biological activities of the soil [8,38]. Likewise, previous studies reported that topography and slope positions can introduce heterogeneity in soil properties [1,6,8]. The highest recovery levels of soil physical properties including soil bulk density, total porosity, macroporosity, penetration resistance, and aggregate stability were observed under the TS treatment. However, the recovery values of soil physical properties in the TS treatment were still lower than the values found in the UND areas within a four-year period following machine traffic. These results are consistent with findings from Moorman et al. [39], stating that the particulate and dissolved materials displaced across the slope position from the summit to the toeslope resulted in soil detachment and erosion in the summit and backslope, and sediment deposition in the toeslope. Similarly, our results revealed that the recovery values of soil physical properties and soil moisture were significantly higher in the TS position than in the S and BS positions.

Our results highlight the importance of slope positions on the recovery levels of compacted soil properties over a 4-year period after traffic. Following harvesting operations, soil bulk density and penetration resistance remarkably increased in the machine operating trails in the tested slope positions (i.e., TS, BS, and S), compared to the UND areas. Consistent with our findings, several studies reported that soil physical properties (e.g., bulk density and penetration resistance) were significantly increased after machine traffic [10,29,40]. Four years after skidding operations, the recovery levels of soil bulk density and penetration resistance were higher in the TS than in the BS and S treatments, compared to the UND areas. Furthermore, by transporting the eroded materials and organic matter as well as litters from S to the TS position on bare mineral soil, water storage capacity augmented, which in turn suppressed the runoff and soil loss [9,17,41]. Consequently, SOC and soil moisture were enhanced and augmented soil fauna, which in turn resulted in reclamation of soil aggregates [42,43]. In contrast, soil aggregates in the S and BS positions were destructed after ground-based machine traffic and were left directly exposed to raindrop impacts, which led to increased runoff and detached soil particles. The effects from the mechanical stress caused during harvesting operations impaired air permeability and air-filled pore connectivity, which resulted in suppressing the activities of soil fauna as reported by Horn et al. [12], Cambi et al. [44], and Flores Fernández et al. [28].

Four years of litter production and its associated movement on compacted soil, from upper to lower slope positions, are largely responsible to rehabilitate the organic matter content and nutrients cycling in the TS, compared to the S and BS treatments. Hence, the greater decomposition rate of organic material provided a higher release and propagation of nutrients in the TS, compared to the S and BS positions. Significant negative correlation ($p < 0.05$) was observed among SOC content and bulk density. By increasing the organic matter content through a thicker litter layer, the soil bulk density decreased in the TS positions. In turn, the litter layer absorbs rainwater, governing soil temperature and moisture, intercepting throughfall, regulating temperature fluctuations from/to soil surface, and decreasing soil particle detachment. All of these benefits can accelerate the natural rehabilitation of soil bulk density [14,17]. Clay and silt particles were also detached from upper slope positions (i.e., S and BS treatments) and deposited in the lower slope position (i.e., TS), which increased water storage capacity. Results of this study demonstrated that soil particle size distribution was significantly different among the slope positions and those from the UND areas. Because of this relocation of fine particles, the highest sand content was observed in the S treatments, while the highest contents of silt and clay particles were found in the TS treatment. Reasons for this have been described by Marques et al. [45], stating that the S treatment was exposed more to the erosion processes than the TS and BS treatments, which concentrated the sand particles following removal of finer particles.

Our results indicated that soil chemical properties were considerably modified after machine traffic compared to the UND areas, a finding supported by Cambi et al. [44] and Jourgholami et al. [17]. Similar to our findings, Jourgholami et al. [17] reported that soil pH significantly increased after ground-based skidding operations. Specifically, Karaca et al. [1] reported that soil pH and EC values increased from the backslope to the terrace, however, they found no significant differences in available nutrients among the topographic positions (i.e. backslope, footslope, and terrace). Zhu et al. [7] and Lozano-García and Parras-Alcantára [3] also reported that SOC was significantly higher at the toeslope than at the shoulder. The lower C/N ratio of soil was found in the TS followed by S > BS > UND areas. Previous studies reported that the slope position can introduce a microclimate, which in turn regulated soil moisture and solar radiation and resulted in spatial variability of SOC, N, and C/N ratio [3,9,46]. The higher humic and fulvic acids were observed in the TS treatment due to a higher soil moisture availability, which resulted in improved soil physical and chemical properties. Similar to our findings, Fu et al. [47] validated that soil physical and chemical properties levels were higher in the foot slopes than in the middle and lower slopes. The higher soil physical and chemical properties in the TS than S and BS treatments enhanced the earthworm activity and abundances as reported by Jourgholami et al. [13]. Fine root biomass was found to be higher in the TS followed by BS and S treatments. This is likely caused by the increase of soil bulk density and penetration resistance in the S and BS treatments, which decreased the elongation and propagation of plant roots [10,44].

4.2. Soil Microbial Properties and Enzyme Activity

Physical and environmental factors such as leaching, amount of organic matter, clay transfer, and soil moisture are affected by the position of slope [3,7]. In line with the current study, many studies reported a positive correlation between soil microbial biomass and activities with SOC [9]. Accordingly, the greater amounts of available nutrients detected in the TS than those recorded in the S and BS can be attributed to the larger litter input and flux from the upper slopes. Hence, the high litter decomposition rates due to the higher microbial activity can influence organic matter processes and nutrient cycling, which is in agreement with the results of Fu et al. [47] and Zhu et al. [7]. Therefore, soil microbial biomass and activity were more pronounced in the TS as compared to the S and BS treatments. In contrast, the higher soil temperature and the lower moisture content and litter input resulted in a less appropriate environment, thus declining the soil microbial communities in the S and BS treatments, compared to the TS treatment. Consistent with our findings, Baldrian and Stursova [22] and Yang et al. [25] reported that the spatial variation of soil moisture due to the different slope position can be affected by microbial biomass and activity. Our results showed that higher levels of SMR, MBC, NH_4^+, NO_3^-, N mineralization, and MBN were reported in the TS treatment as compared to the S and BS treatments. Therefore, the machine operating trails located at the TS position were attributed to the greater availability of nutrients for soil microbial communities. The TS position can supply favorable ambient conditions and high soil moisture as well as suitable quality of substrate [9,48]. In contrast, the S and BS positions showed prominently lower values of SOC and N microbial properties (e.g., MBC, NH_4^+, NO_3^-, N mineralization, and MBN) than those observed in the TS, which indicates an unfavorable ambient condition.

In accordance with findings from Kang et al. [46], Liu et al. [48] and Fazlollahi Mohammadi et al. [9], our results accentuated the significance of topography features, and in particular slope position, in augmenting divergence in enzyme activity. Enzyme activity in soils is dependent on the microbial communities (e.g., soil microorganisms) and soil physical, chemical, and biological properties, which are commonly regulated by tree species [22]. The highest enzyme activity (i.e., urease, acid phosphatase, arylsulfatase, invertase, and ß-N-acetylglucosaminidase) measured in the TS treatment can be largely explained by the higher soil moisture in the TS than in the BS and S treatments. This increased enzyme activity indicated a more favorable environment for soil microbial activities and biomass as well as abundance. Similarly, Fazlollahi Mohammadi et al. [9] reported that the higher soil moisture and deposition of organic matter increased the enzyme activity more significantly in the TS treatment than in the S and BS treatments. Fazlollahi Mohammadi et al. [9] also stated that the reduced quantity of substrate in the S and BS positions was the most important factor for suppressing enzyme activity. The result of the current study revealed that the important drivers influencing enzyme activity were the organic matter and soil moisture. The lower slope positions are associated with the higher soil moisture [49] and the greater organic matter deposition [48], which lead to higher SOC and N in the substrate for soil microorganism activities [9].

Results of Pearson's correlation in this study demonstrated that the activity levels of urease, acid phosphatase, arylsulfatase, invertase, and ß-N-acetylglucosaminidase showed a significant positive correlation ($p < 0.05$) with soil moisture content, SOC and N microbial biomass, NH_4^+, and NO_3^-, which was compatible with previous studies [9,48,49]. However, soil physical properties (i.e., bulk density), pH, and C/N ratio were negatively correlated with enzyme activity. Previous studies revealed that the primary control for enzyme activity is soil pH, and that small changes in pH can have a significant effect on enzyme activity [50,51]. In addition, slope positions had significant influence on the soil physical, chemical, and biological properties as well as SOC and N microbial biomass, which are the important drivers that contributed to enzyme activity, findings that are also supported by Jourgholami et al. [13]. Our hypothesis that slope positions have a significant influence on the physical, chemical, and biological soil properties, as well as enzyme activity of compacted soil in previously trafficked machine operating trails is supported by our data.

The results of the current study could be applied in several regions with similar stand conditions (large-diameter deciduous trees, sloped terrain, close-to-nature forest management) since the slope position is a concept that is well accepted as a driver of soil physio-chemical and hydrological processes and their associated impacts on creating diverse soil properties. Hence, understanding the soil restoration dynamics on the different catena positions of a slope is valuable information that can be used to efficiently plan the off-road traffic of ground-based forest machines.

5. Conclusions

In the present study, the effects of slope positions (e.g., summit (S), backslope (BS), and toeslope (TS)) on the recovery levels of compacted soil properties and enzyme activity were tested on machine operating trails four years after they had been trafficked by ground-based forest machines, compared to the UND areas. Results revealed that the highest recovery of soil physical, chemical, and biological properties was found in the TS rather than in the S and BS treatments, but the levels were still lower than those recorded in the UND areas, even 4 years after ground-based skidding operations. Our results confirmed that soil microbial and enzyme activity differed significantly among slope positions and the UND areas. The microbial and enzyme activities of compacted soil were higher in the TS than in the S and BS treatments. However, the full recovery of these properties as compared to those measured at the UND areas did not occur over a 4-year period in the study area.

Author Contributions: M.J., A.R., and G.Z.A. conceived and designed the experiments; M.J. and A.R. performed the experiments and analyzed the data; all authors wrote the paper.

Funding: This research was funded by the Deputy of Research, University of Tehran grant number 28514. The work was also supported by the German Research Foundation (DFG) and the Technical University of Munich (TUM) in the framework of the Open Access Publishing Program.

Acknowledgments: We would like to acknowledge the assistance of the field crew; Ghodrat Daneshvar from Kheyrud Forest Research Station, Nowshahr, Ali Nasirian; MSc student for his assistant the in-laboratory analysis. We also want to thank the Editor and three anonymous reviewers for their constructive comments for the improvement of this paper.

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

References

1. Karaca, S.; Gülser, F.; Selçuk, R. Relationships between soil properties, topography and land use in the Van Lake Basin, Turkey. *Eurasian J. Soil. Sci.* **2018**, *7*, 115–120. [CrossRef]
2. Wang, S.; Wang, X.; Ouyang, Z. Effects of land use, climate, topography and soil properties on regional soil organic carbon and total nitrogen in the Upstream Watershed of Miyun Reservoir, North China. *J. Environ. Sci.* **2012**, *24*, 387–395. [CrossRef]
3. Lozano-García, B.; Parras-Alcantára, L. Variation in soil organic carbon and nitrogen stocks along a toposequence in a traditional Mediterranean olive grove. *Land Degrad. Dev.* **2014**, *25*, 297–304. [CrossRef]
4. Krasilnikov, P.V.; García Calderón, N.E.; Sedov, S.N.; Vallejo Gómez, E.; Ramos, B.R. The relationship between pedogenic and geomorphic processes in mountainous tropical forested area in SierraMadre del Sur, Mexico. *Catena* **2005**, *62*, 14–44. [CrossRef]
5. Seibert, J.; Stendahl, J.; Sørensen, R. Topographical influences on soil properties in boreal forests. *Geoderma* **2007**, *141*, 139–148. [CrossRef]
6. Brubaker, S.C.; Jones, A.J.; Lewis, D.T.; Frank, K. Soil properties associated with landscape position. *Soil Sci. Soc. Am. J.* **1993**, *57*, 235–239. [CrossRef]
7. Zhu, M.; Feng, Q.; Zhang, M.; Liu, W.; Qin, Y.; Deo, R.C.; Zhang, C. Effects of topography on soil organic carbon stocks in grasslands of a semiarid alpine region, northwestern China. *J. Soils Sediments* **2018**, *19*, 1640. [CrossRef]
8. Chen, L.F.; He, Z.B.; Du, J.; Yang, J.J.; Zhu, X. Patterns and environmental controls of soil organic carbon and total nitrogen in alpine ecosystems of northwestern China. *Catena* **2016**, *137*, 37–43. [CrossRef]
9. Fazlollahi Mohammadi, M.; Jalali, S.G.; Kooch, Y.; Said-Pullicino, D. The effect of landform on soil microbial activity and biomass in a Hyrcanian oriental beech stand. *Catena* **2017**, *149*, 309–317. [CrossRef]
10. 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]
11. Labelle, E.R.; Jaeger, D. Soil compaction caused by cut-to-length forest operations and possible short-term natural rehabilitation of soil density. *Soil Sci. Soc. Am. J.* **2011**, *75*, 2314–2329. [CrossRef]
12. Horn, R.; Vossbrink, J.; Becker, S. Modern forestry vehicles and their impacts on soil physical properties. *Soil Till. Res.* **2004**, *79*, 207–219. [CrossRef]
13. Jourgholami, M.; Ghassemi, T.; Labelle, E.R. Soil physio-chemical and biological indicators to evaluate the restoration of compacted soil following reforestation. *Ecol. Indic.* **2019**, *101*, 102–110. [CrossRef]
14. Etehadi Abari, M.; 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]
15. Cambi, M.; Certini, G.; Neri, F.; Marchi, E. The impact of heavy traffic on forest soils: A review. *For. Ecol. Manag.* **2015**, *338*, 124–138. [CrossRef]
16. Labelle, E.R.; Poltorak, B.J.; Jaeger, D. The role of brush mats in mitigating machine-induced soil disturbances: An assessment using absolute and relative soil bulk density and penetration resistance. *Can. J. For. Res.* **2019**, *49*, 164–178. [CrossRef]
17. 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]
18. Ampoorter, E.; De Schrijver, A.; De Frenne, P.; Hermy, M.; Verheyen, K. Experimental assessment of ecological restoration options for compacted forest soils. *Ecol. Eng.* **2011**, *37*, 1734–1746. [CrossRef]
19. Poltorak, B.J.; Labelle, E.R.; Jaeger, D. Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats. *Soil Till. Res.* **2018**, *179*, 96–104. [CrossRef]
20. Jourgholami, M.; Labelle, E.R.; Feghhi, J. Efficacy of leaf litter mulch to mitigate runoff and sediment yield following mechanized operations in the Hyrcanian mixed forests. *J. Soils Sediments* **2019**, *19*, 2076–2088. [CrossRef]
21. Bottinelli, N.; Capowiezc, Y.; Ranger, J. Slow recovery of earthworm populations after heavy traffic in two forest soils in northern France. *Appl. Soil. Ecol.* **2014**, *73*, 130–133. [CrossRef]
22. Baldrian, P.; Stursova, M. Role of Enzymes in Maintaining Soil Health. In *Soil Enzymology*; Shukla, G., Varma, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 61–73.

23. Dick, R.P.; Myrold, D.D.; Kerle, E.A. Microbial biomass and soil enzyme activities in compacted and rehabilitated skid trail soils. *Soil Sci. Soc. Am. J.* **1988**, *52*, 512–516. [CrossRef]
24. Bandick, A.K.; Dick, R.P. Field management effects on soil enzyme activities. *Soil Biol. Biochem.* **1999**, *31*, 1471–1479. [CrossRef]
25. Yang, Y.; Geng, Y.; Zhou, H.; Zhao, G.; Wang, L. Effects of gaps in the forest canopy on soil microbial communities and enzyme activity in a Chinese pine forest. *Pedobiologia* **2017**, *61*, 51–60. [CrossRef]
26. Barreiro, A.; Fontúrbel, M.T.; Lombao, A.; Martín, A.; Vega, J.A.; Fernández, C.; Carballas, T.; Díaz-Raviña, M. Using phospholipid fatty acid and community level physiological profiling techniques to characterize soil microbial communities following an experimental fire and different stabilization treatments. *Catena* **2015**, *135*, 419–429. [CrossRef]
27. 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*, 453–465. [CrossRef]
28. Flores Fernández, J.L.; Hartmann, P.; Schäffer, J.; Pulhmann, 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]
29. Fründ, H.-C.; Averdiek, A. Soil aeration and soil water tension in skidding trails during three years after trafficking. *For. Ecol. Manag.* **2016**, *380*, 224–231. [CrossRef]
30. Gee, G.W.; Bauder, J.W. Particle-size analysis. In *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*; Klute, A., Ed.; Soil Science Society of America: Madison, WI, USA, 1986; pp. 383–411.
31. Danielson, R.E.; Southerland, P.L. *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods*, 2nd ed.; ASA, SSSA: Madison, WI, USA, 1986; pp. 443–460.
32. Kemper, W.D.; Rosenau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis. Part I Physical and Mineralogical Properties*, 2nd ed.; Klute, A., Ed.; Agronomy Monograph; American Society of Agronomy, Inc., Soil Science Society of America: Madison, WI, USA, 1986; Volume 9, pp. 425–442.
33. Walkley, A.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
34. Vance, E.D.; Brookes, P.C.; Jenkinson, D.S. An extraction method for measuring soil microbial biomass-C. *Soil Biol. Biochem.* **1987**, *19*, 703–707. [CrossRef]
35. 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]
36. Kolberg, R.L.; Rouppet, B.; Westfall, D.G.; Peterson, G.A. Evaluation of an in situ net soil nitrogen mineralization method in dryland agroecosystems. *Soil Sci. Soc. Am. J.* **1997**, *61*, 504–508. [CrossRef]
37. Schinner, F.; Von Mersi, W. Xylanase-, CM-cellulase-and invertase activity in soil: An improved method. *Soil Biol. Biochem.* **1990**, *22*, 511–515. [CrossRef]
38. Hancock, G.R.; Murphy, D.; Evans, K.G. Hillslope and catchment scale soil organic carbon concentration: An assessment of the role of geomorphology and soil erosion in an undisturbed environment. *Geoderma* **2010**, *155*, 36–45. [CrossRef]
39. Moorman, T.B.; Cambardella, C.A.; James, D.E.; Karlen, D.L.; Kramer, L.A. Quantification of tillage and landscape effects on soil carbon in small Iowa watersheds. *Soil Till. Res.* **2004**, *78*, 225–236. [CrossRef]
40. Goutal, N.; Renault, P.; Ranger, J. Forwarder traffic impacted over at least four years soil air composition of two forest soils in northeast France. *Geoderma* **2013**, *193–194*, 29–40. [CrossRef]
41. Chen, J.S.; Chiu, C.Y. Effect of topography on the composition of soil organic substances in a perfumed sub-tropical montane forest ecosystem in Taiwan. *Geoderma* **2000**, *96*, 19–30. [CrossRef]
42. 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.
43. Liu, Y.; Zhang, J.; Yang, W.; Wu, F.; Xu, Z.; Tan, B.; Zhang, L.; He, X.; Guo, L. Canopy gaps accelerate soil organic carbon retention by soil microbial biomass in the organic horizon in a subalpine fir forest. *Appl. Soil Ecol.* **2018**, *125*, 169–176. [CrossRef]
44. Cambi, M.; Hoshika, Y.; Mariotti, B.; Paoletti, E.; Picchio, R.; Rachele, R.; Marchi, E. Compaction by a forest machine affects soil quality and *Quercus robur* L. seedling performance in an experimental field. *For. Ecol. Manag.* **2017**, *384*, 406–414. [CrossRef]
45. Marques, K.P.P.; Demattê, J.A.M.; Miller, B.A.; Lepsch, I.F. Geomorphometric segmentation of complex slope elements for detailed digital soil mapping in southeast Brazil. *Geoderma Reg.* **2018**, *14*, e00175. [CrossRef]

46. Kang, S.; Lee, D.; Lee, J.; Running, S. Topographic and climatic controls on soil environments and net primary production in a rugged temperate hardwood forest in Korea. *Ecol. Res.* **2006**, *21*, 64–74. [CrossRef]
47. Fu, B.J.; Liu, S.L.; Chen, L.D.; Lu, Y.H.; Qiu, J. Soil quality regime in relation to land cover and slope position across a highly modified slope landscape. *Ecol. Res.* **2004**, *19*, 111–118. [CrossRef]
48. Liu, W.; Xu, W.; Han, Y.; Wang, C.; Wan, S. Responses of microbial biomass and respiration of soil to topography, burning, and nitrogen fertilization in a temperate steppe. *Biol. Fertil. Soils* **2007**, *44*, 259–268. [CrossRef]
49. Jencso, K.J.; McGlynn, B.L.; Gooseff, M.N.; Wondzell, S.M.; Bencala, K.E. Hydrologic connectivity between landscapes and streams: Transferring reach and plot scale understanding to the catchment scale. *Water Resour. Res.* **2009**, *45*, W04428. [CrossRef]
50. Frankenberger, W.T., Jr.; Johanson, J.B. Effect of pH on enzyme stability in soils. *Soil Biol. Biochem.* **1982**, *14*, 433–437. [CrossRef]
51. Wang, A.S.; Angle, J.S.; Chaney, R.L.; Delorme, T.A.; McIntosh, M. Changes in soil biological activities under reduced soil pH during *Thlaspi caerulescens* phytoextraction. *Soil Biol. Biochem.* **2006**, *38*, 1451–1461. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).