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Changes in Soil's Chemical and Biochemical Properties Induced by Road Geometry in the Hyrcanian Temperate Forests

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Abstract: Forest roads play an important role in providing access to forest resources. However, they can significantly impact the adjacent soil and vegetation. This study aimed to evaluate the effects of road geometry (RG) on the chemical and biochemical properties of adjacent soils to assist in environmentally friendly forest road planning in mountainous areas. Litter layer, canopy cover, soil organic carbon (SOC) stock, total nitrogen (TN), the activity of dehydrogenase (DHA), and urease (UA) enzymes at a 0–20 cm soil depth were measured by sampling at various distances from the road edge to 100 m into the forest interior. The measurements were done for three road geometries (RG), namely straight, curved, and bent roads, to ensure data heterogeneity and to reflect the main geometric features of the forest roads. Analysis of variance (ANOVA) showed that the effects of RG on the measured variables were statistically significant. Spearman's correlation test clearly showed a strong positive correlation between environmental conditions, SOC, TN, DHA, and UA for given RGs. Based on piecewise linear regression analysis, the down slope direction of the straight and the inside direction of bent roads accounted for the lowest and highest ranges of ecological effects, respectively. The results of this study contribute to our understanding of the environmental effects brought about by road geometry, which can be important for forest road managers when applying the best management practices.

Keywords: soil; biogeochemistry; enzyme; organic carbon; total nitrogen; forest road; road-effect zone; Hyrcanian temperate forests

1. Introduction

Although transportation infrastructure is an integral and inseparable element of development and growth, it directly impacts the structure and functioning of the surrounding ecosystems. There is no doubt that building transportation infrastructure plays a significant role in an ecosystem's degradation, reconstruction, and reconfiguration [1]. In general, roads, a typical example of transportation infrastructure, affect the biotic and abiotic environment in their surroundings [2–5]. In forested areas, roads are constructed to facilitate forest management practices and also to provide access to forest resources. Although roads can lead to an increase in tree growth along their edges [6], they can also result in natural disturbances [7] by leading to habitat fragmentation [8], inducing invasion of pests, diseases, and exotic species [9], increasing erosion and sediment yield [10,11], changing vegetation diversity and biomass components in adjacent forest stands [4,12,13], and influencing the soil's physical and chemical properties [5,14].

As an essential part of the ecosystem for vegetation development, forest soil is influenced by climate, plants, and animal species that control its physical, chemical, hydrological, and biological properties, and by engineering activities such as road construction and forest operations [4,15,16]. These activities directly or indirectly affect forest soil properties by changing the microclimate on adjacent areas [17]. By changes in vegetation and plant diversity in the adjacent forest, forest roads have an impact on the stock of soil organic carbon (SOC) and total nitrogen (TN) deposition, and therefore on the soil's physical and chemical properties [5,14,18,19]. The N cycle is linked to the carbon cycle, since the carbon–nitrogen interplays constrain the amount, distribution, and turnover rate of the carbon in soil [20,21]. Due to the fact that human activities considerably influence SOC stock and TN deposition cycles in forest areas, it is important to add to the understanding of the interactions between these two elements in forest soils [22,23]. Moreover, all types of soils contain a group of enzymes whose activity may be used to characterize the vital processes of given soils [24]. This is because their activity provides useful information about the bacterial status and biochemical soil conditions, while the enzymes themselves are characterized as sensors of organic matter decomposition [25,26], showing quick responses to natural and anthropogenic disturbances [27]. Soil dehydrogenase (DHA) is one of the main soil enzymes participating in and assuring the full sequence of biochemical pathways within a soil biogeochemical cycle [28]. Urease (UA) is closely connected to the organic matter decomposition of debris and plant species and nutrient cycling [29]. It is widely found in nature and plays an essential role in the C-N cycle [30]. Due to the important role that soil enzymes are playing in the energy transfer via the decomposition of organic matter and nutrient cycling [31], they are often used as a measure of disturbances, such as those related to environmental conditions and forest management practices, and as a direct measure of the soil microbial activity [32].

The Hyrcanian temperate forest of Iran is a deciduous forest located on the northern slope of the Alborz Mountains [33]. *Fagus orientalis* Lipsky (oriental beech) is one of the dominant tree species in the region, which supplies timber annually [34–36]. Depending on the local topography and mainly on the slope, forest roads along this forest are subject to a number of changes in their geometry (straight, curved, and bent). Several studies have reported various distances to the forest interior at which the forest roads impact the soil components, such as, for example, C and N [5,14,19]. Edge orientation, particularly in mountainous regions, can affect the amount of light penetration into the forest stands [7,17]. In addition, variability in road geometry (RG) can lead to different amounts of earthwork, affecting the forest soil in the surrounding area. Since we still need to construct new roads for both utilizing and protecting forest stands, attempts are being made in forest road planning and assessment to achieve a well-organized road network with minimum negative impacts by considering technical, economic, and environmental criteria [37–40]. However, to the best of our knowledge, there has not been any study regarding the effect of a forest road on soil enzyme activity, and there was no attempt to quantify the ecological effects of RG on the forest soil. It is assumed that the geometry of forest roads can influence the soil enzyme activity by affecting the SOC stock and TN deposition. However, no research has addressed RG when investigating road ecological effects on forest soils. Therefore, data is needed to estimate the ecological impact of RG variability on the surrounding forest soil. This will further help the forest road managers to plan an efficient road network while mitigating the resulting environmental impacts. In this study, we test the hypothesis that the road ecological effect zone is associated with road geometric attributes and roadsides. Hence, this study aimed at: (1) Assessing the effect of forest roads on SOC stock, TN cycling, and the activities of two enzymes (DHA and UA) in relation to the road geometry (RG) and roadside; (2) Predicting how far into the forest interior does the effect of each

RG reach; (3) Designing a spatial model of road ecological effects to be applied in road planning for the conservation of forest soil biology.

2. Materials and Methods

2.1. Study Site

This study was carried out along forest roads accessing a mixed *F. orientalis*, *Carpinus betulus* (L., common hornbeam) and *Acer velutinum* (Boiss., velvet maple) stand located in the first district of Dr. Bahramnia Research and Experimental Forest Station of the Gorgan University of Agricultural Sciences and Natural Resources, Northern Iran (Figure 1). Geographically, the forest stand covers an area of about 712 hectares, and contains 13 parcels. The forest is extended from the north at an altitude of 780 m a.s.l. to the south at an altitude of 1010 m a.s.l. The area has a humid climate, with the maximum and minimum rainfall occurring in February and August, respectively; June, July, August, and September are the driest months of the year. Forest road network is 11.7 km in length and has a density of 16.4 m per hectare, with an average road spacing of about 550 m. The road network was constructed approximately 20 years ago.

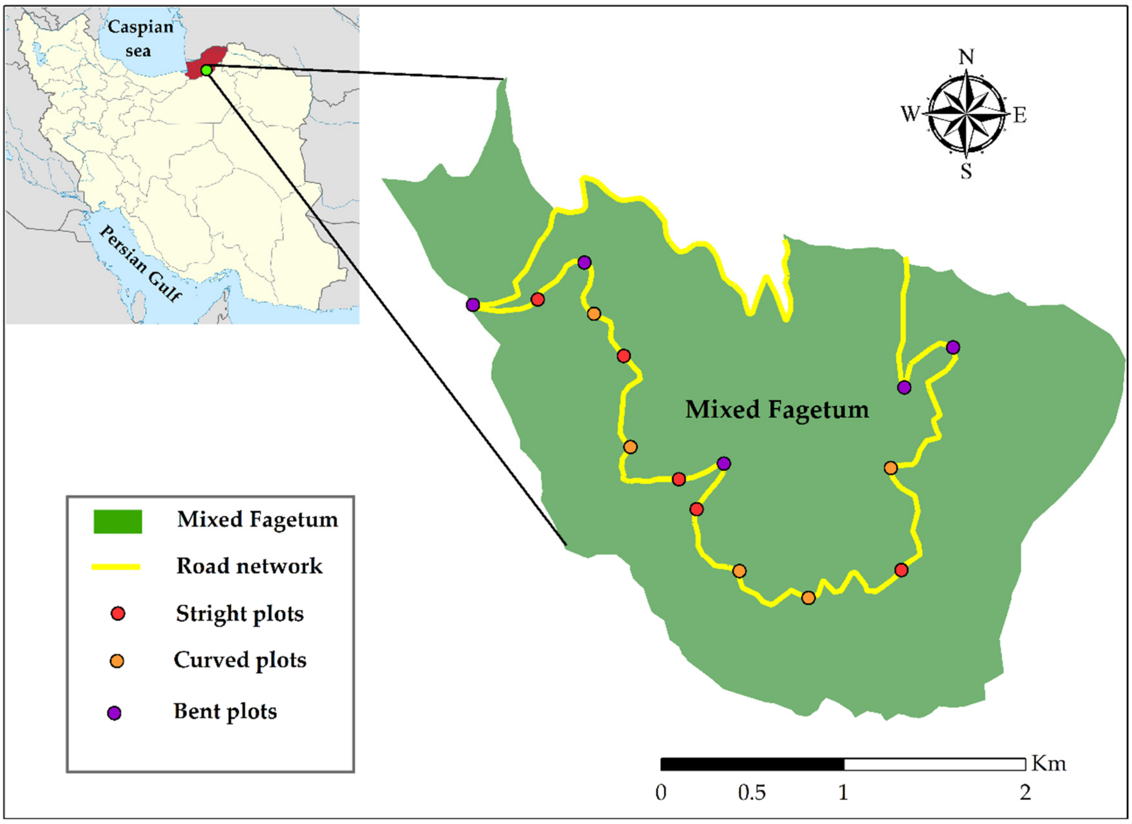

Figure 1. Area of study and transects' location along the road.

2.2. Experimental Setup

Fifteen points (5 per each road geometric configuration, Figure 1) were selected along the forest road network to establish transects on the up and down slopes. When placing the transects, it was attempted to consider hillslopes with similar slope angles. The main descriptive statistics of the up and down slopes (RS) are given in Table 1 on RG categories. In each point, two transects with a length of 100 m were established from the road edge into the forest interior [3,4,14,41], perpendicularly to the road's center axis; one transect was oriented towards the up slope and the other towards the down slope. Along each transect, one-by-four-m plots were placed at zero (i.e., road edge), 5, 10, 15, 20, 30, 40, 50, 60, 80, and 100 m from the road edge [42,43], so that their width was oriented along the transect and their length was perpendicular to the transect (Figures 2 and A1). For control samples, 5 plots located at 150 m in the forest interior were randomly established near the transects so as to ensure that their slope was near zero.

Table 1. Description of mean (±standard error) slope (%) on each roadside (RS) for the studied road geometries (RG).

RS	RG		
	Straight	Curved	Bent
Up slope (%)	24 (±3.1)	28.8 (±3.6)	31.4 (±2.9)
Down slope (%)	21 (±3.2)	28.7 (±3.3)	29.9 (±4.3)

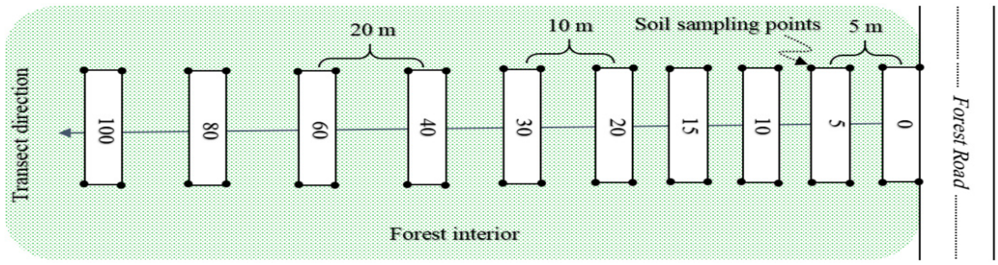

Figure 2. Transect direction and soil sampling design from the road edge into forest stand.

To estimate the stock of SOC (mgC/g soil^{-1}), TN (%), and activity of soil enzymes—DHA (µg TPF g^{-1} soil h^{-1}) and UA (µg N g^{-1} soil h^{-1})—, soil samples were taken in dry days from the four corners of each plot at 0–20 cm in depth. All samples were placed in the icebox and transported to the laboratory. At the laboratory, parts of the soil samples were stored at a temperature of 4 °C with the purpose of running biochemistry analysis. The remaining parts were air-dried, and, after sieving through a 2 mm mesh, were analyzed to check the present soil nutrients [5,21]. Walkley and Black [44] and Kjeldahl [45] methods were used to estimate the SOC and TN in the soil. The amount of DHA (µg TPF g^{-1} soil h^{-1}) in micrograms of formazan phenyl and UA (µg N g^{-1} soil h^{-1}) in micrograms of nitrogen were estimated by using enzyme–substrate reaction and a spectrophotometer [46]. To account for the relation between micro-environmental conditions and soil properties, litter layer (mm), soil temperature (°C), and pH were measured at the corners of each plot using the design shown in Figure 2. Soil temperature was measured using a digital probe-thermometer sensor (TFA Dostmann, Model 30.1048, Ottersberg, Germany). The pH was analyzed in H_2O using the potentiometric method [47]. Canopy cover was estimated by analyzing photos taken in the middle of each plot, using an EOS 750D DSLR camera (Canon, Tokyo, Japan) equipped with fisheye Sigma lens (15 mm f/2.8 EX DG) mounted on a leveling device. Photographs were analyzed using the Gap Light Analyzer software (GLA software, Ver. 2.0) [5,48–50].

2.3. Statistical Analysis

Piecewise linear regression (PLR) method was used to estimate the distance threshold for the road ecological effect into the forest stand. The PLR divided by a breaking point (i.e., turning point) the data into two parts, and the trends (slopes) before and after the breaking point were different [51,52]. PLR is proved to properly define ecological thresholds resulting from human disturbance [52–58]. The normality of the data was checked using the Shapiro–Wilk test. Then, the one-way analysis of variance (ANOVA) was used to investigate the contribution of factors such as the up and down slopes, RG (i.e., straight, curved, and bent), and their interaction on the properties of the surrounding soil. The 'agricolae' package was used in the R environment (version 3.5.0) to perform the Duncan's means comparison and grouping test ($p < 0.05$) to find differences among the means by considering the RG [59].

Independent sample t-tests were used to compare the difference between the measured soil variables for each roadside (hereafter RS) for a given RG ($p < 0.05$). Finally, the Spearman's rank correlation coefficients (rs) were analyzed to examine the correlations between the response variables and environmental and soil's physicochemical variables (litter layer, soil temperature, canopy cover, C/N, and soil pH). The statistical analysis was carried out in R, version 3.5.0 [58]; PLR was implemented in the 'segmented' package of R (Regression Models with Breakpoints).

2.4. Road Effect Zone

An average road-effect zone for each RG was obtained based on the data generated by PLR regression for the studied variables. The mean values were used to build a buffer zone around the road segments representing the ecological effect zone for each RG. The buffer zones were simply created by using the buffer function in the Arc Map environment (version 10.2).

3. Results

3.1. Environmental Conditions

As shown in Table 2, RS and RG had significant effects on SOC ($p < 0.001$) and TN ($p < 0.01$). Moreover, there were significant effects of the RS (both up and down slopes) and RG (straight, curved, and bent) on the activity of DHA ($p < 0.01$) and UA ($p < 0.001$) enzymes (Tables 2 and 3). The interaction term showed that the effects of RS and RG were significant on TN ($p < 0.001$) and UA ($p < 0.01$), while no significant effects were found on SOC and DHA (Table 2).

Table 2. Effect of roadsides (RS), road geometry (RG), and their interaction on the SOC, TN, DHA, and UA.

Soil Variables	RS	RG	Interaction
SOC (mg × g soil^{-1})	16.55 ***	71.65 ***	1.27 ^{ns}
TN (%)	11.17 **	88.30 ***	22.46 ***
DHA (µg TPF g^{-1} soil h^{-1})	21.02 **	7.92 **	2.00 ^{ns}
UA (µg N g^{-1} soil h^{-1})	43.02 ***	13.47 ***	12.07 **

Note: ^{ns} means not significant; significance levels are indicated by asterisks: ** $p < 0.01$; *** $p < 0.001$.

Table 3. Description of mean (±standard deviation) values of soil variables for each RS (up and down slopes) by considering different RGs (straight, curved, and bent).

Soil Variables	Roadside (RS)	Road Geometry (RG)		
		Straight	Curved	Bent
SOC (mg × gsoil^{-1})	Up slope	2.70 ± 1.06B *	4.78 ± 2.40A *	4.96 ± 2.40A *
	Down slope	1.94 ± 0.67B *	3.07 ± 1.38A *	3.48 ± 2.27A *
TN (%)	Up slope	0.287 ± 0.10C ^{ns}	0.335 ± 0.13B ^{ns}	0.595 ± 0.30A *
	Down slope	0.255 ± 0.09B ^{ns}	0.302 ± 0.11B ^{ns}	0.399 ± 0.16A *
DHA (µg TPF g^{-1} soil h^{-1})	Up slope	5.47 ± 1.99B ^{ns}	7.05 ± 3.20A *	7.97 ± 3.27A *
	Down slope	5.05 ± 1.61A ^{ns}	5.41 ± 2.07A *	5.55 ± 2.34A *
UA (µg N g^{-1} soil h^{-1})	Up slope	6.16 ± 1.49A ^{ns}	7.80 ± 2.55A *	8.92 ± 2.81A *
	Down slope	5.31 ± 1.77A ^{ns}	5.99 ± 2.31A *	6.07 ± 2.27A *

Note: capital letters denote significant differences ($p < 0.05$) among RG (in each RS). * and ^{ns} indicates significant and no significant differences ($p < 0.05$) between RS (in each RG), respectively.

The mean values of soil properties were higher on the up-slope direction (Table 3). Statistical analysis, however, showed that only the value of SOC was significantly different ($p < 0.001$) at the two RS (up slope = 2.70 ± 1.06 and down slope = 1.94 ± 0.67) of straight roads (Table 3). For curved roads, there was no significant difference between TN values (up slope = 0.335 ± 0.13 and down slope = 0.302 ± 0.11), while the mean values of all variables were significantly different in the bent roads (Table 3). Moreover, there was an increasing gradient in the mean values of soil properties from straight to bent RGs (Table 3).

Soil properties (SOC, TN, DHA, and UA) depend on and were positively correlated with the changes in environmental factors (distance to the road, litter layer, and canopy cover) for given RGs (Figure 3). A significant negative correlation was also detected between the soil's pH and temperature and the measured variables, while C/N did not show a consistent association with the soil variables (Figure 3).

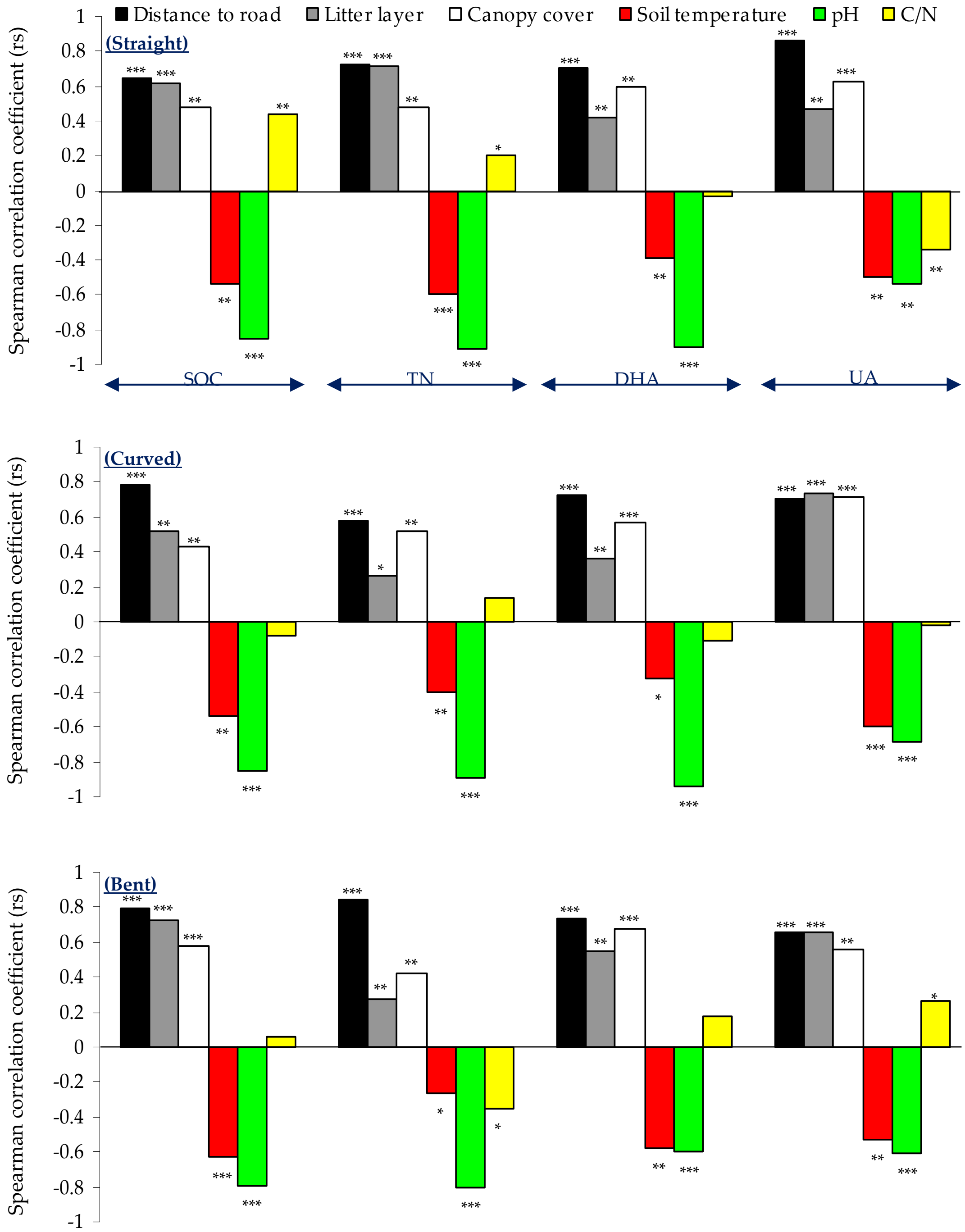

Figure 3. Spearman correlations between the soil environmental and physicochemical variables for each RG (straight, curved, and bent). Significance levels are indicated by asterisks: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3.2. Extent of the Road Effects

The results of PLR analysis showed that the value of each soil variable has increased from the road edge to the forest interior, where it became relatively constant (Figure 4; Table 4). However, the lowest value of each variable was observed at the road edge (i.e., zero m), and the effect of each RG was different.

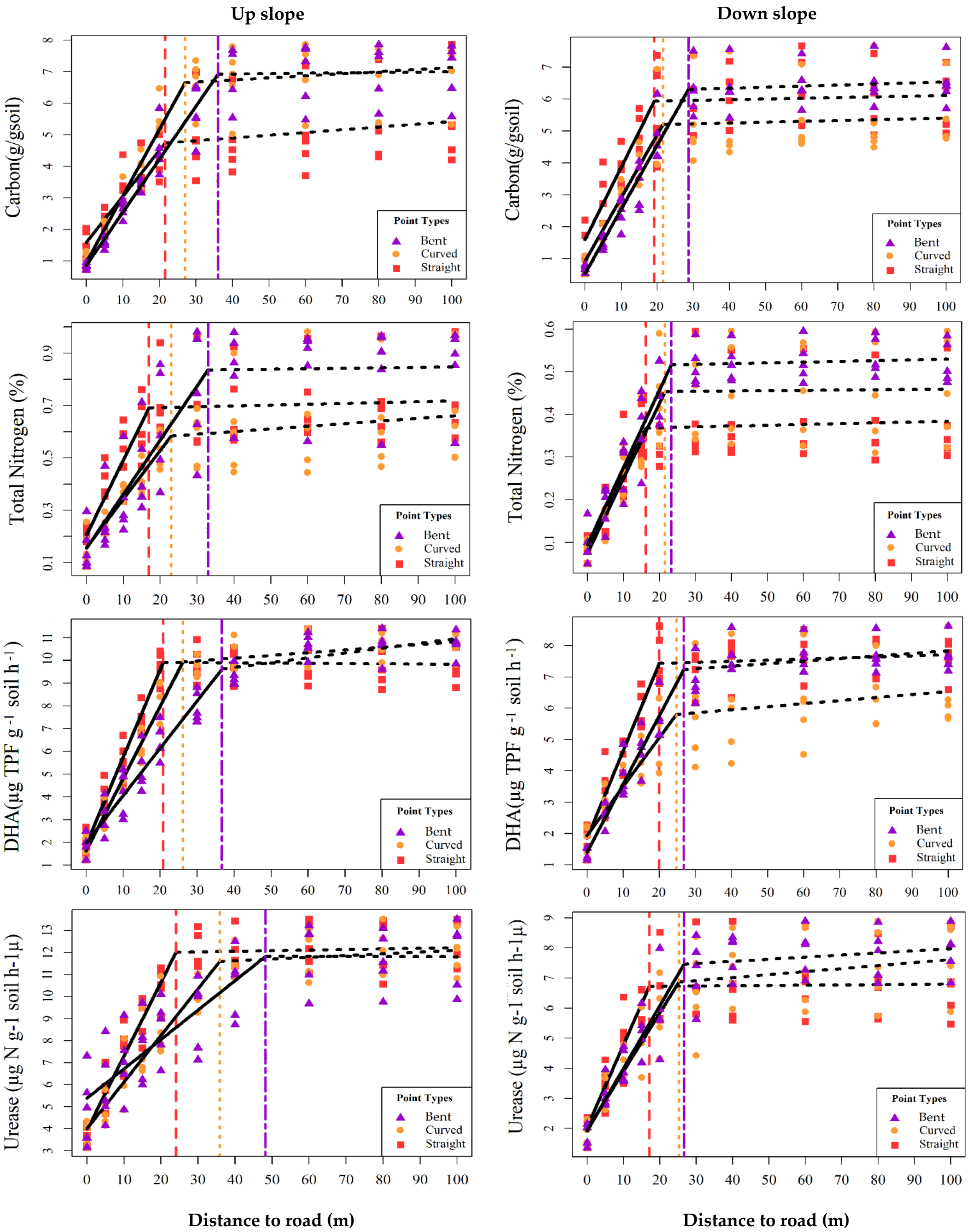

Figure 4. Road geometry (straight, curved, and bent) range effect on the SOC, TN, DHA, and UA into the forest interior by considering road sides (up and down slopes). Color dashed lines denote road effect-zones for different road geometries (red = straight; orange = curved; purple = bent). The black continuous and dash lines denote pre and post breaking point (i.e., road effect-zone), respectively.

Table 4. Average (±standard error) road-effect zone (m) on soil biochemical variables for different roadsides and road geometries.

Soil Variables	Roadside (RS)	Road Geometry (RG)		
		Straight (m)	Curved (m)	Bent (m)
SOC	Up slope	21.58 (±3.66)	27.02 (±2.19)	36.04 (±2.50)
	Down slope	19.18 (±2.37)	21.56 (±2.43)	28.62 (±2.00)
TN	Up slope	16.94 (±2.40)	22.95 (±3.54)	33.01 (±5.76)
	Down slope	16.27 (±2.39)	21.56 (±2.60)	23.28 (±2.62)
DHA	Up slope	20.85 (±1.00)	26.17 (±1.16)	36.75 (±2.36)
	Down slope	19.98 (±1.37)	24.77 (±3.95)	26.76 (±1.66)
UA	Up slope	24.04 (±1.56)	35.90 (±2.90)	48.23 (±1.78)
	Down slope	17.08 (±1.94)	25.22 (±4.17)	26.63 (±4.08)

Therefore, the edge effect of the road network concerning the RG was found to be quite different. Based on the results, the total length from the road to the forest interior affected by road-induced impacts was greater for the up slope than for the down slope (Figure 4 and Table 4). The largest effects were observed at the up slope (inner-side area) of bent roads, while the smallest effects were observed at the down slope of straight roads (Figure 4 and Table 4). The results show that RG was not responsible for any significant difference in the extent of the road ecological effects at the down slope of forest roads. In particular, changes in the activity of UA were observed to a distance of 48.23 m (SE = ± 1.78 m) at the inner-side of bent roads, while, at the outer-side of bent roads, the changes were evident to a distance of 26.63 m (SE = ±4.08 m) (Figure 4 and Table 4).

According to PLR results, the shortest distances on which roads affected TN were 16.94 m (±2.40 m) and 16.27 m (SE = ±2.39 m) for straight roads' up and down slopes, respectively (Figure 4 and Table 4). The greatest ecological threshold for DHA and UA soil parameters were observed for the bent RG (Figure 4 and Table 4). In general, the greatest road ecological effect was observed for UA, while the lowest effect was obtained for TN (Figure 4 and Table 4).

3.3. Road Ecological Effect Zone

The studied road length was divided into 105 segments to determine the area affected by roads. Ultimately, an area of 90.94 ha (12.7%) of the total area was influenced by forest roads (Figure 5).

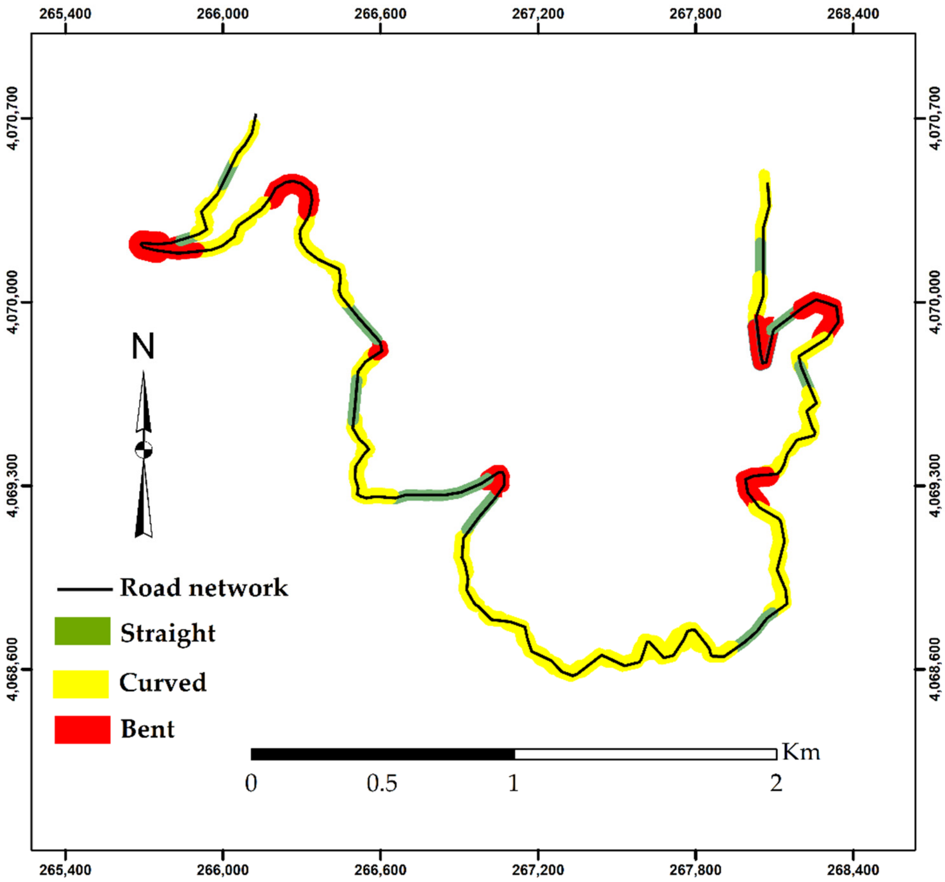

Figure 5. Road-effect zone on soil properties depending on road geometry (RG)—an example.

4. Discussion

According to the results, the chemical and biochemical properties of the forest soils changed from the road edge into the forest interior, and there was a substantial increase in the amount of SOC and TN. Forest roads disturb forest soils and vegetation and remove an important part of the forested areas along their path [60]. Roads increase the quantity of runoff and erosion rates in the surroundings, which could cause the displacement of much material and salts from the road to a long distance [61]. In addition, due to the canopy removal and change in the canopy cover along the forest roads, the incoming organic matter through litter loss in plants and organic matter decomposition around these roads will be affected [17]. Tree species was proved to be a factor, which has the potential of altering the chemical and biochemical properties of soils through leaf litterfall [23,28,62]; therefore, roads can affect the stock of SOC [63] by changing the composition and structure of forest vegetation cover. Moreover, selective logging in the area could cause soil compaction, leading to more runoff and erosion along the forest road, therefore it will contribute to a reduction in SOC [64]. Some researchers have reported that the composition and diversity of vegetation directly affect C and nutrient cycling through the provision of litter with distinct physicochemical properties; it also has indirect impacts on C through the modification of the decomposition environment [19,65]. Contents and stocks of SOC and TN in the forest floor were higher for beech stands than other broadleaf species, particularly maple and lime trees [66]. For as much as we know, road construction provides better near-road growing conditions for light-demanding species such as maple and common hornbeam; hence, the amount of carbon and TN may decrease around the road.

In addition, blowing wind and the movement of heavy equipment for logging and transportation can influence the spatial distribution of falling leaves and litter to a considerable distance from the forest roads [67]. A decrease in SOC stocks at the forest edges resulting from edge-induced tree mortality was also reported for a temperate forest [68]. The corridor opened by the road can affect wind speed and direction and, in turn, can have remarkable effects on the frequency of windblown trees. This will change the amount of light entering the forests and reduce the SOC stock, which is likely to be attributed to the fact that organic carbon and soil nitrogen in the forest ecosystem cycles are provided mainly through the residues of the herb and leaves. Loss of SOC around the road was also described for other activities (e.g., road building), inducing the disturbance of soil and scattering of particles [69].

Changes in TN around the forest road showed a trend which was similar to SOC. It had the lowest rates at the edge of the straight road and then increased with distance from the road. Literature reviews have indicated that soils were warmer and drier at the road edge than their forest interior counterparts, which can affect the decomposition rates of SOC [62,63]. Forest roads cause significant changes in the amount of light entering the forest through gaps in tree canopy along their path [5], which can explain the increase in soil temperature around the road [1,15,70,71]. Furthermore, a rapid increase in soil moisture immediately after rainfall events [31,72–74] can decrease the synthesis of nitrogen around the forest road, as there is less interception and more rainwater into the soils [75], which is due to the canopy removal around the roads. In addition, previous research has highlighted that light is one of the most critical factors in forests, as changing its intensity alters the usual cycle of the forest ecosystem [76]. By changing the amount of light entering the forest stands, forest roads cause an edge effect on the forests [5,17] through the removal or alteration of canopy cover. An increase in the extent of road effects on the inner-side of bent roads is due to a higher removal of the canopy in both RSs, which can increase the effect zone by up to a distance of 36 m for SOC and 33 m for TN.

The activity of the studied soil enzymes (i.e., DHA and UA) increased with the distance to the road at both sides. Biochemical properties of the soil, such as the enzyme activity, are more sensitive than the physical and chemical properties, and react quickly to environmental changes [30,32,77]. Therefore, these properties are often used as indicators of soil quality [78]. Management activities such as road construction disrupt macro accumulates, accentuate the labile SOC mineralization, and affect the soil organic matter [79]. There is a strong linkage between the stock of SOC and enzyme activities affected by various factors (e.g., pH, moisture, and temperature) within the same soil layers [18,79]. Another possible explanation is that, typically, forest soil is rich in organic matter coming from plant litter. According to the aggregation of organic materials, enzymes contributing to the decomposition of organic matter play an important role in forest soils [28,47]. Based on our findings, soil organic matter increased with distance from the forest road edge. In turn, higher amounts of soil organic matter increase the activity of soil microorganisms and DHA enzyme activity [78]. From straight to bent road geometries, soil compaction increases in the surrounding areas. This compaction reduces the soil microbial activities, affects soil microbial communities and DHA enzyme activity [80], and can justify the lower DHA activity in the proximity of the road. Our finding showing the reduction in UA activity at the road edges during summer further supports an earlier report which showed that the correlation between soil temperature and UA was positive in winter and negative in summer [81].

RG was mentioned as an important criterion in road network planning and assessment [37–40]; yet, the interactions of RG and adjacent forest stands have rarely been understood. Our results showed a strong correlation between RG and environmental conditions such as changes in canopy cover, soil temperature, litter layer, and pH. Although the results showed a generally increasing trend for the values of soil properties measured from the edge of the road to the forest interior, the slope of the gradients and the RS effect range differed for different RGs. For example, changes in SOC stock for a straight road were found to occur at a distance of 21.6 m into the forests, while the figure was 36 m for the inner-side of bent roads. The results of the comparison of DHA and UA represent a further influence of the bent road on the activity of these enzymes. An increase in the amount of light due to canopy removal on both sides can increase the ambient temperature, which is an important factor for an increased activity of soil microorganisms and for the sustained activity of DHA and UA enzymes in the forest soil [31].

Our results showed that the PLR method could be useful for finding the thresholds where the increasing/decreasing trend changes or experiences a nearly constant state [82,83]. In fact, the breaking point of the regression line obtained by PLR defines the width of the road-effect zone. Although the trend of changes in data points can be represented by the use of a curve (nonlinear regression or a broken quadratic regression), setting up a PLR model has been found to provide better results [52–59,83,84]. Considering the RG, local climate, topography, type of forests, and forestry practice related to road building, and according to PLR analysis, about 13% of the area can be affected by forest road-induced ecological impacts. Although the estimated ecological effect zone may not appear to be severe, its future dynamics may be of concern. Being aware of such effects in the earlier stages of road planning will help prevent or at least mitigate the unpredictable changes in the forest environment in a long-term timeline.

Although our study investigates road ecological effects based on rarely-addressed variables with focus on the road geometry, it should be noted that a full understanding of the road-effect zone in temperate forests requires a long-term monitoring of aspects such as soil properties, tree regeneration, wildlife, moss, fungi, and lichen diversity. As the intensity of the road-effect zone is somehow context-dependent, the extent and magnitude of the road-effect zone found in this study can only be extended to forest types and climate zones similar to those of the site taken into the study.

5. Conclusions

The effects of forest roads on the surrounding soil properties can be different depending on their specific geometry. Moreover, these effects may vary from the up to the down slope. Based on this work, straight roads can extend their impact to a distance of 16.30 m, while the effects from the inner-side of a bent road can go as far as 48.23 m from the road edge into the forest interior. One probable reason could be the changes in the amount of available light and the degree of soil disturbance, which are likely to be different for various road geometries. Therefore, employing methods capable of accurately estimating such effects in the earliest stages of road planning can help achieve a close-to-nature-based road network with negligible adverse effects. Based on this work, the road-effect zone can be used as an additional criterion in road planning and assessment to reduce the impact of the road network on the forest environment.

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Appendix A

Figure A1. Description of the sampling concept used in this study. Upper panel: an example of a road section showing the up and down slope and the points and distances at which the sampling plots were placed. Legend: red lines—conceptual geometry of the road, green dots—points at which control plots were placed, orange dots—points at which the plots were placed from the road edge to forest interior, red dots—points at which the plots were placed at the road edge; Lower panel: examples of transect placing for the three road geometries taken into study. Legend: red and green dots have the same meaning as in the upper panel, red lines—transects, gray—forest roads.

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