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Mountain recreation impact on changes in soil penetration resistance of spruce forests

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Abstract. The uniqueness of the Carpathian Mountain Forest ecosystems, a large part of which belongs to nature conservation areas, attracts a significant number of visitors annually. Intensive tourist flow on popular hiking trails leads to recreational digression, topsoil compaction, development of erosion processes and deterioration of forests. The research aims to determine the impact of recreation as an external mechanical impact on soil compaction by determining the soil penetration resistance under the canopy of predominant spruce stands. For this purpose, soil penetration resistance was measured with a penetrometer along two hiking trails within the root layer of the soil at four measuring sites at different distances from the hiking trail. In general, under the canopy of a forest stand, the soil cover is not homogeneous and the obtained penetration resistance values are characterised by considerable variability. It was revealed that for the "Zelene village – Uhorski skeli rocks" hiking trail in the areas close to the path (up to 20 m) there is a significant increase in soil penetration resistance compared to remote areas: at a depth of 10 cm it

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doubles, at a depth of 20 cm – by 20-40%, but with further deepening, the penetration resistance level off. At the same time, for the more popular "To Mount Pip Ivan Chornohirskyi" hiking trail, in the area adjacent to the trailbed, the penetration resistance reaches 19.6 kg·cm^{-2} in the upper 10 cm layer, and at a depth of 30 cm, it peaks at 37.8 kg·cm^{-2} (over 3 MPa), which affects the root spatial distribution of spruce forests. Intensive erosion processes due to soil compaction with an increase in soil penetration resistance above 60 kg·cm^{-2} (~6 MPa) are observed on the trailbed. The practical significance of the results obtained, and the established patterns is to complement existing methods for assessing the degree of recreational digression in mountainous conditions and can be the basis for designing measures to regulate tourist flows and restore affected areas

Keywords: soil compaction; digression; hiking trail; penetrometer; ecosystem

Introduction

Mountain ecosystems are the most valuable in Europe by species richness and ecological importance (14.8% of the Carpathians are in Ukraine), which requires nature conservation areas establishment on territory. At the same time, the preserved uniqueness of mountain ecosystems compared to commercial forests attracts visitors, and the number of visitors is constantly growing (State Statistics..., 2021). According to the terms of use of protected areas (The Law of Ukraine..., 1992), recreation requires compliance with the protection plans of protected natural complexes and a differentiated approach according to functional zoning. In the area of regulated or stationary recreation, any activity that may lead to environmental degradation and decrease the recreational value of the territory of the national nature park is prohibited.

The Carpathian region is characterised by various types of tourism, including mountain tourism (hiking), skiing, cycling, natural history, equestrian, cultural, recreational, and health tourism, etc. C. Pickering *et al.* (2010) concluded that equestrian tourism, jeeping and cycling, and off-road rallies cause the most damage on hiking trails. These impacts include soil degradation, changes in vegetation cover, reduction of biodiversity, fragmentation of forests, and concentration and development of tourist infrastructure. For mass tourism in mountain national parks, there are problems with regulation and compliance with the rules of stay in protected areas, which are slow to recover to ecological balance. In general, the most significant negative impacts on mountain ecosystems occur when tourism is uncontrolled.

The mismatch between demand, the existing functional zoning and the recreational capacity of the Carpathian territories affects natural communities due to the excessive concentration of visitors in the most popular tourist destinations. As a result, a high degree of recreational degradation is observed in some areas, which is primarily reflected in the deterioration of the soil condition and physical properties and leads to irreversible changes in the vegetation cover. J. Toivio *et al.* (2017) found that disturbed soil fosters to decrease in the forest ecosystems productivity, which leads to the loss of ecosystem services, especially regulating, supporting and resource provisioning. Forest soils have lower strength and lower bulk density compared to soils of open areas (pastures), which makes them more sensitive to external mechanical stresses (Blanco-Canqui *et al.*, 2005; Bormann & Klaassen, 2008). X. Hao *et al.* (2008) noted that the assessment of soil changes under anthropogenic impact is based on soil penetration resistance, density, and porosity. Even slight compaction can affect important ecosystem processes and lead to the deterioration of soil chemical and/or physical properties (Ampoorter *et al.*, 2007; S. Yao *et al.*, 2015). D. Sinnett *et al.* (2008) found that soil compaction leads to reduced porosity, reduced nutrient mineralisation rates, modified structure, and thus impeded root development. The processes of soil compaction have a cumulative effect. Long-term soil compaction affects not only aeration but also changes soil moisture regime. D. Jordan *et al.* (2003) stated that under significant mechanical stress, the growth rate and penetration capacity of roots decrease, which leads to a decrease in the rate of water and nutrient absorption.

External mechanical impact on the soil increases its penetration resistance (Frey *et al.*, 2011; Cambi *et al.*, 2016). Soil penetration resistance is a physical property of soil that depends on its bulk density, texture (Imhoff *et al.*, 2016), moisture content (Junior *et al.*, 2014), porosity (Holthusen *et al.*, 2018), structural particle size, pH, mineral and organic content. The study of soil penetration resistance due to external mechanical impact is important for assessing recreational load (Budakova *et al.*, 2021).

The Carpathian National Nature Park (CNNP) is characterised by forest ecosystems represented mainly by spruce stands (Kravchynskyi *et al.*, 2018). The ecological resilience of spruce forests is declining and is associated with significant sensitivity to global climate change (Lavnyi & Pelukh, 2019), and the development of tourism activities in the region add pressure on forest ecosystems. As a result of high recreational impact, the above-ground vegetation is disturbed, and the upper soil layers containing the root system of European spruce are compacted and destroyed (Brusak & Malets, 2018). Following N.V. Yorkina *et al.* (2020), the stage of recreational degradation in forest natural complexes is determined based on a description of the state of the grass and moss cover, forest litter, tree stand, understorey, and the recreation coefficient. The work of V. Brusak (2018) allows to estimate the recreational digression of the micro terrain of hiking trails by the volume of material removed from 1 m^2 of the trailbed. However, the study of the impact of recreational activities on changes in the physical properties of the root-contained soil layer is not complete.

The research aims to assess changes in the soil penetration resistance of spruce stands in the Carpathians, caused by external mechanical stresses from recreational impacts.

Materials and Methods

Sample plots are in forest stands within the Ivano-Frankivsk region (Fig. 1), which represents the main part of the Ukrainian Carpathians. More than 40% of the Carpathian region is covered by forests and 24% of the region's mountain forests are classified as nature reserve fund of Ukraine (Kiseliuk *et al*. 2009).

Spruce forests occupy 79% of the Carpathian NNP forests and 73% of them are natural. Four sample plots were established at an altitude between 1030 m and 1095 m a.s.l. within the pure spruce high-altitude vegetation belt. The coordinates and characteristics of the study plots are given in Table 1.

To assess the degree of impact of recreational activity on the territory of the Carpathian NNP and adjacent tourist sites, the soil penetration resistance values along two hiking trails were measured and analysed. Penetration resistance measurements were carried out using a LAN-M PRO penetrometer (Ukraine). This is the most common approach for assessing the soil penetration resistance (Dexter *et al.*, 2007). The LAN-M PRO penetrometer provides soil penetration resistance measurements every 2.5 cm soil profile depth. Soil penetration resistance was measured in the upper 40 cm soil layer, due to the peculiarities of the stands root systems distribution under the canopy in which the measurements were conducted. All data were collected throughout September 2021 for all studied stands. Soil penetration resistance was determined along two trails: "Zelene village – Uhorski skeli rocks" (SP1, SP2, SP3) and "To Mount Pip Ivan Chornohirskyi" (SP4). The penetration resistance measurements were taken with a gradual remoteness from the trail line away into the forest ecosystems (Fig. 2). Thus, the sample plot SP4 is located adjoint to the "To Mount Pip Ivan Chornohirskyi" hiking trail (5 m from the centre). For the "Zelene village – Uhorski skeli rocks" hiking trail, 3 temporal sample plots were established, including SP1 (5 m from the centre) adjacent to the trail line, and SP3 (40 m from the centre) and SP2 (20 m from the centre) located deep in the forest.

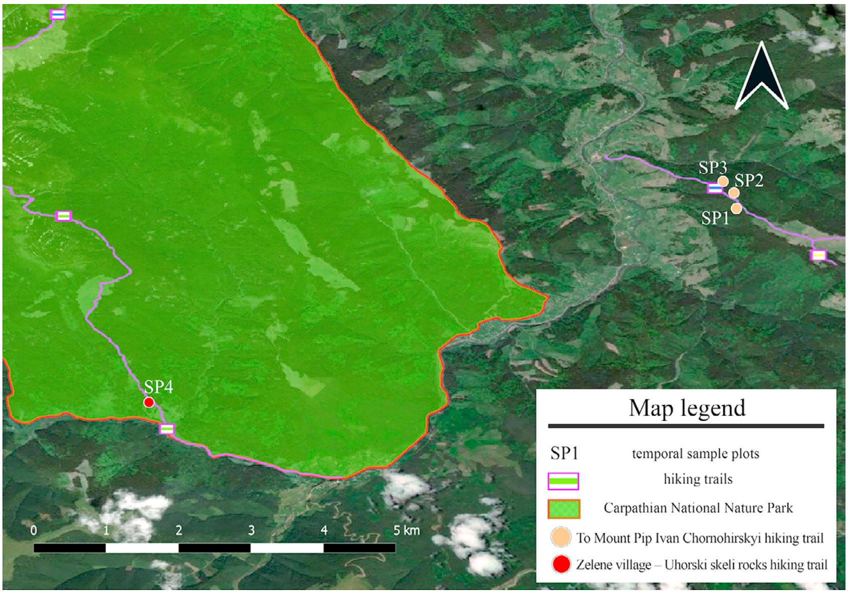

Figure 1. Location of sample plots on hiking trails

Source: compiled by the authors based on QGIS geoinformation system

Table 1. General characteristics of the sample plots in spruce stands

TSP	Altitude, m a.s.l.	Distance to trail	Coordinates	Slope steepness, deg.	Slope exposure	Age, years	Dominant species (%)	Site index	Mean height, m	Mean diameter, cm
"Zelene village – Uhorski skeli rocks" hiking trail										
SP1	1095	5	48.041077°N 24.776265°E	<2	South-West	48	80% NS-B	I^{b}	25.4	32.4
SP2	1090	20	48.041410°N 24.776077°E	<2	North-East	67	93% NS-B	I^{a}	26.4	28.3

Table 1, Continued

TSP	Altitude, m a.s.l.	Distance to trail	Coordinates	Slope steepness, deg.	Slope exposure	Age, years	Dominant species (%)	Site index	Mean height, m	Mean diameter, cm
SP3	1040	40	48.043020°N 24.773406°E	8	North-East	62	86% NS-B	I[a]	24.9	26.7
"To Mount Pip Ivan Chornohirskyi" hiking trail										
SP4	1030	5	48.004258°N 24.668548°E	18	South	58	100% NS	I[b]	29.3	31.5

Note: TSP – temporal sample plot; sample plots SP1-3 along the "Zelene village – Uhorski skeli rocks" hiking trail, sample plot SP4 is located along the "To Mount Pip Ivan Chornohirskyi" hiking trail; NS – Norway spruce; NS-B – Norway spruce with admixture of European beech
Source: compiled by the authors

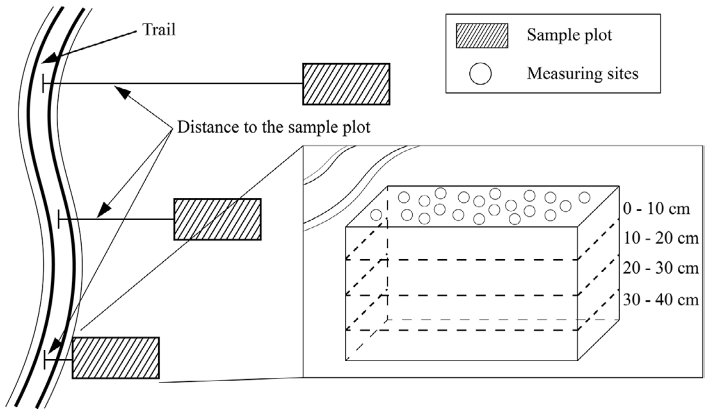

Figure 2. Schematic representation of the experiment setup on the route "Zelene village – Uhorski skeli rocks" hiking trail
Source: compiled by the authors based on QGIS geoinformation system

Penetration resistance measurements on each sample plot were made in 20 replicates, with each measurement made at a distance of at least 1 m from the nearest tree. Abnormally high or low values were not considered in further analysis. In addition, penetration resistance measurements were made in 5 replicates on the trailbeds, opposite to the sample plots. FIELD-M Archive Viewer 2.3 was used to visualise the extrapolated soil penetration resistance values within the sample plots. Differences between soil penetration resistance values at different depths within each sample plot were determined using One-way ANOVA followed by Tukey's HSD post hoc test. Two-Way ANOVA and Tukey's HSD were used to compare the penetration resistance values at different depths along the two trails. All statistical analyses were performed using the R software (Version 4.0.2) (The R Project…, n.d.). The following packages were used to analyse and graphically interpret the results: "psych", "ggplot2", and "ggppubr".

Results and Discussion

The obtained penetration resistance values for all sample plots are highly variable. A brief description of the soil penetration resistance for the sample test SP1 on the "Zelene village – Uhorski skeli rocks" hiking trail is shown in Table 2. This plot is characterised by an increase in soil penetration resistance up to a depth of 22.5 cm from 0.3 to 25.5 kg·cm^{-2}. With the further immersion of the penetrometer in the soil up 40 cm depth, the values levelled off and the mean value ranged from 12.7 to 15.5 kg·cm^{-2}. Similar results were obtained by Budakova *et al.* (2021), where soil penetration resistance values increased significantly up to a depth of 25-30 cm.

Table 2. Descriptive statistics of soil penetration resistance values on the "Zelene village – Uhorski skeli rocks" hiking trail (SP1)

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
0	2.1	2	1.38	0.31	0.39	-1
2.5	4.7	4.6	1.82	0.41	-0.21	-0.6
5	8	8.1	2.23	0.5	0.09	-0.99
7.5	9.7	10.1	3.04	0.68	-1.06	1.6
10	12	12.2	2.28	0.51	-0.03	-1.03
12.5	14.6	14.2	2.98	0.67	0.22	-1
15	14	14	2.36	0.53	0.18	-0.67
17.5	14.3	14	3.5	0.78	0.19	-1.18
20	16.4	17.1	2.94	0.66	-0.25	-1.34
22.5	19.8	20.9	3.83	0.86	-0.04	-1.66
25	19	16.8	4.21	0.94	0.56	-1.19
27.5	15.3	15.4	2.23	0.51	-0.16	-0.43
30	15.3	15.5	2.26	0.53	0.45	0.38
32.5	15.5	15.6	2.08	0.5	-0.53	-0.25
35	12.7	12.8	2.95	0.72	-0.33	-0.03
37.5	15.4	16	2.05	0.5	-0.4	-1.26
40	14.7	14.1	1.49	0.36	0.64	-0.61

Source: compiled by the authors

The graphical interpretation of soil penetration resistance values distribution on the sample plot SP1 on the "Zelene village – Uhorski skeli rocks" hiking trail is shown in Figure 3.

The results of a one-way ANOVA indicate a statistically significant difference between the mean values of soil penetration resistance ($p<0.05$) for different categories of soil depth. Up to a depth of 20 cm, which is characterised by the highest rates of soil root distribution in spruce forests (Yukhnovskyi *et al.*, 2020), there is a sharp increase in soil penetration resistance, and at a depth of 30-40 cm, there is a gradual decrease. The results of the post hoc Tukey's HSD test indicate that the mean values of penetration resistance at a depth of 10-20 and 30-40 cm are similar ($p=0.986$). Thus, the sample plot SP1 is exposed to the highest external impact due to its location. Therefore, the presence of forest litter, vegetation cover, and topsoil are crucial for preventing the erosion processes development (Zuazo & Pleguezuelo, 2008). Following (Zhukov *et al.*, 2021), topography and stand characteristics can explain 30-50% of the spatial variation in soil penetration resistance.

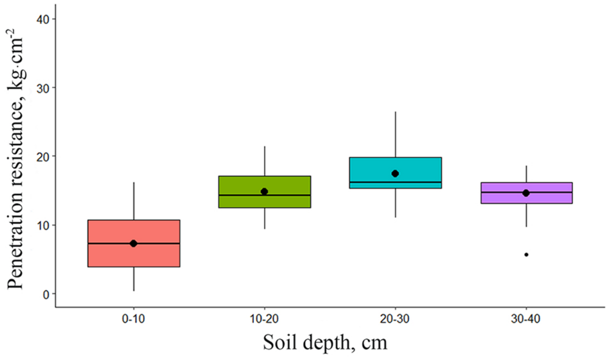

Figure 3. Distribution of soil penetration resistance with depth on the sample plot SP1 on the "Zelene village – Uhorski skeli rocks" hiking trail

Source: compiled by the authors

With 20 m distance from the "Zelene village – Uhorski skeli rocks" hiking trail, sample plot SP2 was surveyed (Table 3).

Similarly, to the SP1, which is directly adjacent to the hiking trail, a trend towards an increase in penetration resistance with depth is observed at a distance of 20 m from the trail. The lowest soil penetration resistance values (1.3 kg·cm^{-2}) were observed in the upper layer at a depth of 5 cm, and the maximum mean value was at a depth of 25 cm, with the further immersion of the penetrometer, the values gradually decrease, i.e., the compaction of the soil decreases. A graphical representation of the soil penetration resistance values distribution at SP2 on the "Zelene village – Uhorski skeli rocks" hiking trail is shown in Figure 4.

Table 3. Descriptive statistics of soil penetration resistance values on the "Zelene village – Uhorski skeli rocks" hiking trail (SP2)

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
0	2.6	2.6	0.91	0.25	0.66	-0.02
2.5	3.7	3.9	0.9	0.25	-0.43	-0.9
5	6.6	6.7	1.34	0.37	-0.13	-0.97
7.5	9.2	10.1	2.16	0.6	-0.66	-0.92
10	12	12.4	2.59	0.72	-0.17	-1.1
12.5	13.6	13	3.74	1.04	0.09	-1.68
15	14.6	14.7	4.14	1.15	-0.36	-1.42
17.5	14.7	17.1	4.82	1.34	-0.46	-1.4
20	14.3	14.8	3.38	1.07	0.13	-1.41
22.5	16.8	16.8	4.33	1.37	0.09	-1.58
25	18.1	18.1	4.82	1.52	0.01	-1.8
27.5	17.6	17.3	5.24	1.66	0.08	-1.55
30	16.8	16.2	5.33	1.69	0.63	-1.13
32.5	15.3	14	5.47	1.73	0.9	-0.75

Table 3, Continued

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
35	14.3	12.5	5.14	1.71	0.92	-0.8
37.5	13.4	11.9	4.58	1.53	1.03	-0.67
40	12.4	11.8	4.94	1.65	0.98	-0.2

Source: compiled by the authors

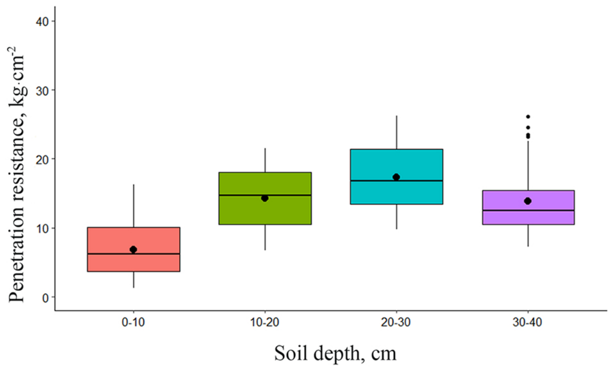

Figure 4. Distribution of soil penetration resistance with depth on the sample plot SP2 on the "Zelene village – Uhorski skeli rocks" hiking trail
Source: compiled by the authors

In general, for the sample plot SP2, there is a sharp increase in soil penetration resistance in the upper layers, which reaches its peak at a depth of 20-30 cm, followed by a gradual decrease at a depth of 30-40 cm. A statistically significant difference ($p<0.05$) was found between the mean values of penetration resistance for different categories of soil layer depths, and according to the results of Tukey's HSD test, no significant differences ($p=0.977$) were found for soil layers 10-20 cm and 30-40 cm.

The most distant from "Zelene village – Uhorski skeli rocks" hiking trail is the SP3 plot. The results of the study of soil penetration resistance values at this site are presented in Table 4.

Table 4. Descriptive statistics of soil penetration resistance values on the "Zelene village – Uhorski skeli rocks" hiking trail (SP3)

Depth, cm	**Descriptive statistics**					
	Mean penetration resistance, kg·cm^{-2}	**Median**	**sd – standard deviation**	**se – standard error**	**Skewness**	**Kurtosis**
0	1.6	1.3	0.69	0.21	0.68	-0.8
2.5	2.6	2.5	0.99	0.31	0.31	-1.31
5	4	4.3	1.8	0.57	-0.06	-1.76
7.5	5.3	4.1	2.93	0.93	0.54	-1.52
10	6.6	6.2	4.24	1.36	0.28	-1.51
12.5	9.7	11	4.62	1.46	-0.65	-1.26

Table 4, Continued

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
15	11.4	12.4	5.02	1.59	-0.63	-1.18
17.5	11.2	13.2	5.16	1.63	-0.32	-1.77
20	11.6	12.9	5.05	1.6	-0.33	-1.21
22.5	13.6	14	3.54	1.12	0.33	-0.21
25	15.2	15.7	3.57	1.13	-0.59	0.61
27.5	15.9	16.6	3.9	1.23	-1.33	1.37
30	15	15.6	4.11	1.3	-0.97	0.39
32.5	14.6	15.3	3.99	1.26	-0.27	-0.71
35	14.2	13.2	4.14	1.31	0.81	-0.18
37.5	15.8	16	4.3	1.36	0.32	-0.75
40	16.7	16.7	4.89	1.55	0.3	-1.3

Source: compiled by the authors

A gradual increase in the soil resistance to penetration is observed up to a depth of 27.5 cm and varies along the entire profile from 0.7 to 24.3 kg·cm^{-2}. The distribution of values by depth indicates the absence of a certain trend in the skewness. The distribution of penetration resistance values at SP3 on the "Zelene village – Uhorski skeli rocks" hiking trail is illustrated in Figure 5.

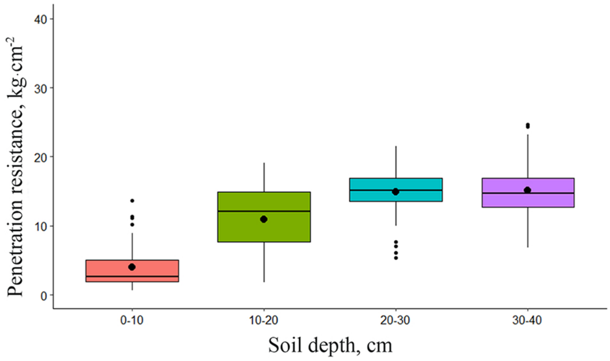

Figure 5. Distribution of soil penetration resistance with depth on the sample plot SP3 on "Zelene village – Uhorski skeli rocks" hiking trail
Source: compiled by the authors

The rapid increase in penetration resistance is observed only up to a depth of 20 cm and then the values have less variability with depth. The mean values of penetration resistance for different depth categories have a statistically significant difference ($p<0.05$) according to the results of One-way ANOVA, but with a depth of more than 20 cm, the mean values of penetration resistance do not differ significantly ($p=0.993$). That is, the soil structure is homogeneous with a gradual increase in its penetration resistance capacity.

The forest environment is extremely heterogeneous, including in the sample plot SP1 (Fig. 6), with the upper soil layers having a loose structure and low penetration resistance.

Under the influence of trees, the greatest variations in soil penetration resistance were observed compared to the influence of herbaceous vegetation (Kunakh *et al.*, 2022). Furthermore, the "Zelene village – Uhorski skeli rocks" hiking trail is also subject to periodic use of forestry vehicles. Forestry activities and recreational pressure accelerate the compaction of the soil and lead to a decrease in soil moisture, impaired infiltration, and reduced moisture available for plant growth (Deng *et al.*, 2003). The use of logging machines or illegal use of trucks on hiking trails has a significant impact on soil structure: overall soil porosity decreases by 20% and the number of macropores decreases by 50-60% (Teepe *et al.*, 2004). Importantly, according to S. Yaşar Korkanç (2014), 500 times of walking along the trail almost doubles the penetration resistance in its upper layer, from 3.78 kg·cm^{-2} to 6.06 kg·cm^{-2}.

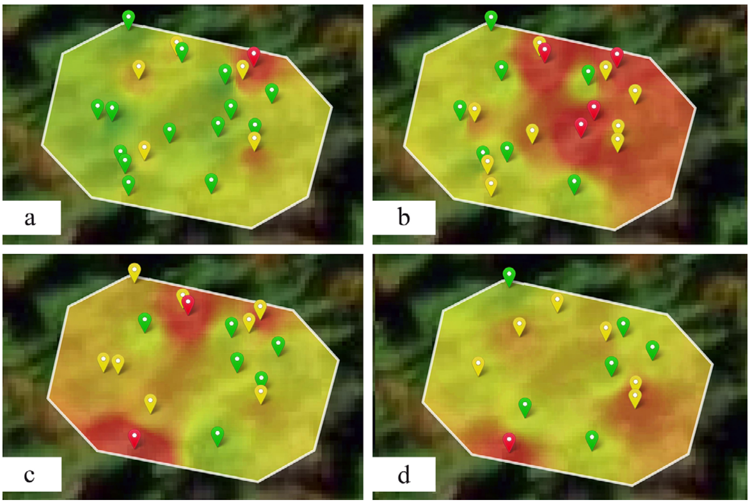

Figure 6. Extrapolated soil penetration resistance data at SP1 along the "Zelene village – Uhorski skeli rocks" hiking trail: a) 10 cm; b) 20 cm; c) 30 cm; d) 40 cm
Source: compiled by the authors

The sample plot SP4 is located along the "To Mount Pip Ivan Chornohirskyi" hiking trail in the Carpathian National Nature Park and under regular recreational use. According to the results of short-term monitoring, periodic illegal use of trucks for recreational purposes was recorded on this trail. The trail is characterised by significant soil layer erosion (up to 1 m relative to the level of undisturbed soil profile under the forest canopy), which causes inconvenience to tourists who use the trailside as a detour, thus disturbing the structure of the ground vegetation cover and forest litter. The central part of the tourist trails undergoes the greatest changes in the soil environment and vegetation condition. Due to the significant soil compaction, it was not possible to determine the penetration resistance values on the trailbed itself, as the topsoil compaction exceeded the maximum permissible values of the penetrometer (60 kg·cm^{-2} or 6 MPa). The penetration resistance of the soil was measured in the area adjacent to the edges of the trail (Table 5).

Table 5. Descriptive statistics of soil penetration resistance values on the "To Mount Pip Ivan Chornohirskyi" hiking trail (SP4)

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
0	4.2	2.3	3.31	1.25	0.46	-1.78
2.5	10.1	10.4	3.68	1.36	-0.4	-1.03
5	15.2	16.4	4.03	1.52	-0.19	-1.79
7.5	16.6	16.2	2.07	0.78	-0.37	-1.47
10	19.7	17.9	5.24	1.98	0.39	-1.79
12.5	23	23.7	4.47	1.69	-0.4	-1.29
15	25.6	26.3	4.48	1.69	-0.06	-1.85
17.5	29.2	29.4	3.74	1.41	0.34	-1.42
20	30.9	31.6	6.25	2.36	0.1	-1.93
22.5	27	25.7	2.64	1	0.34	-1.92
25	25.4	25.5	0.96	0.36	0.01	-1.86
27.5	27.6	29.1	4.63	1.75	-0.02	-1.99
30	27.2	25.7	5.45	2.06	0.84	-0.73
32.5	27.8	29.6	3.99	1.51	-0.53	-1.73
35	28.2	29.3	3.6	1.36	-0.24	-1.51
37.5	29.9	31.3	5.17	1.95	-0.44	-1.6
40	26.5	27.4	2.62	0.99	-0.73	-1.19

Source: compiled by the authors

In the sample plot SP4, a sharp increase in the penetration resistance in the upper layers is present. The highest value was 37.8 kg·cm^{-2} at a depth of 30 cm. The summary results of soil penetration resistance are illustrated in Figure 7. The upper 0-10 cm layer has a wide range of values. At the depth of 10-20 cm, there is a significant soil compaction and an increase in the penetration resistance. One-way ANOVA showed no significant differences (p>0.05) for the resistance values at the depths of 10-20 cm, 20-30 cm, and 30-40 cm. Only the upper 0-10 cm layer had significantly lower penetration resistance values.

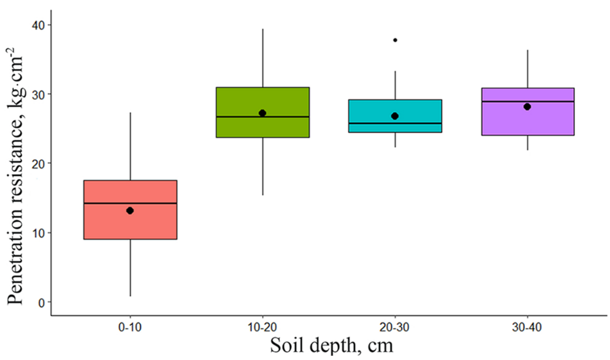

Figure 7. Distribution of soil penetration resistance indicators with depth on the sample plot SP4 on the "To Mount Pip Ivan Chornohirskyi" hiking trail

Source: compiled by the authors

Thus, all the studied sites under the spruce canopy are characterised by an increase in soil penetration resistance with depth. With a decrease in the distance to the trailbed the mean values of penetration resistance increase throughout the depth of the soil profile. Similar results on the trend of increasing soil penetration resistance while approaching the trail are reported by V.S. Budakova *et al.* (2021) for recreational facilities in the urban ecosystem. Moreover, J. Deng *et al.* (2003) determined that the closest areas to hiking trails are most affected by recreation in the Zhangjiajie National Forest Park in China.

Two-Way ANOVA and Tukey's HSD test were used to compare the penetration resistance values along the hiking trails at different depths. For the sample plots on the "Zelene village – Uhorski skeli rocks" hiking trail (SP1 and SP2), there was no statistically significant difference across the entire depth of the soil profile, despite the heterogeneity of the soil profile at SP1. The soil penetration resistance values in the top 20 cm layer were significantly different for SP1 and SP3, for SP3 and SP2 ($p<0.05$), which may indicate the presence of external mechanical impacts on the soil along the same trail. With increasing depth, the difference in penetration resistance is completely levelled. The soil penetration resistance along the popular "To Mount Pip Ivan Chornohirskyi" hiking trail (SP4) is significantly higher compared to the areas on the "Zelene village – Uhorski skeli rocks" hiking trail. The reasons for this are recreational use, soil erosion along the trail, illegal use of vehicles, and the lower thickness of the soil profile and bedrock outcrops. On the popular "Prypir-Zaroslyak" and "To Mount Hoverla" hiking trails, according to V. Brusak (2018) for the Carpathian NNP, at the final stage of topography transformation the disturbance of the soil cover (denuded surface) extends to a depth of 60 cm. According to this research, the volume of soil material washed from a trail segment can reach 0.5 m^3 per 1 m^2 and cause a catastrophic level of degradation.

According to (Sinnett *et al.*, 2008), soil penetration resistance in the range of 2 to 3 MPa (approximately 20-30 kg·cm^{-2}) significantly impedes the development of root systems. Penetration resistance above 3 MPa causes a sharp decrease in the root distribution, as 70% of roots are formed in soil layers with a penetration resistance of less than 2 MPa and 90% of roots in soils with a penetration resistance of less than 3 MPa. The results obtained for the two hiking trails indicate significant fluctuations in soil penetration resistance. Along the "To Mount Pip Ivan Chornohirskyi" hiking trail, the penetration resistance values vary from 13.2 kg·cm^{-2} (~1.3 MPa) in the upper layers to 28.1 kg·cm^{-2} (~2.8 MPa) at depth. The compaction of surface soil layers due to recreational activities significantly impede the spread of European spruce root systems in mountain forest ecosystems. Penetration resistance values of more than 2 MPa mainly occur at a depth of more than 20 cm, where decrease in the European spruce root distribution was observed (Yukhnovskyi *et al.*, 2020).

The impact of soil compaction on its ability to function as a vital ecosystem has been studied in more detail than the duration of soil recovery processes. For soils, where forestry activities are performed , the predicted duration for the full recovery of the soil to its natural state can be 50-70 years (Mohieddinne *et al.*, 2019). The process of restoring soil cover in the upper layers (0-40 cm) can take decades, especially for areas disturbed by large vehicles, and without additional restoration treatments (Pousse *et al.*, 2022). According to (Goutal *et al.*, 2013; Bonnaud *et al.*, 2019), the processes of restoring the natural density and penetration resistance capacity of the soil are much faster than the restoration of water and air regimes. At the same time, the restoration of the upper soil layers to their natural state is faster compared to the deeper layers. The restoration of natural resistance is influenced by both physical factors and the activities of living organisms.

Conclusions

The forests of the Ukrainian Carpathians on the territory of the nature reserve fund, especially the National Nature Parks, are attractive objects for various types of tourism, including uncontrolled tourism. Conventional methods for assessing the impact of recreation on forest ecosystems are based on a description of the state of living ground cover, forest litter, tree stand, understory and undergrowth, and the recreation coefficient, but little regard for changes in the soil profile.

In mountainous conditions, active recreational activities cause soil compaction, which increases penetration resistance, reduces soil erosion resistance, and affects forest growth conditions. Soil compaction reduces porosity, which inhibits the development of European spruce root systems. Soil penetration resistance values of more than 3 MPa, which are limiting for root distribution, are observed in areas of forests adjacent to hiking trails and are characteristic of a depth of 10-20 cm. Directly on the hiking trails, there is a complete trampling of vegetation and forest litter, and erosion processes are developing, which is caused by significant soil compaction with a penetration resistance more than 60 $kg{\cdot}cm^{-2}$ (~6 MPa). In the studied areas, there is a heterogeneity of soil penetration resistance values, which is influenced by both environmental factors (occurrence of bedrock, activity of soil fauna, root systems, etc.) and anthropogenic factors (tourism, forestry machinery). Soil penetration resistance decreases by 20-40% with the distance from the hiking trails into the spruce forest. The decrease in penetration resistance indicates a decrease in external mechanical impact on the upper soil layers, living ground vegetation and root systems of trees.

The Ukrainian Carpathians have favourable conditions for ecotourism development, but sustainable development need to be promoted as well as careful use of recreational potential, and therefore comply with the regulations for visiting nature conservation areas.

The study of soil compaction processes creates the prerequisites for a regulatory assessment of the recreation impact and facilitates the scientific basis for planning measures to promote the restoration of the soil physical condition and restore forest ecosystems natural state.

Conflict of Interest

The authors declare no conflict of interest.

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Вплив гірської рекреації на зміну твердості ґрунту ялинових лісів

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Анотація. Унікальність Карпатських гірських лісових екосистем, значна частина яких належить до природно-заповідних територій, приваблює щороку значні обсяги відвідувачів. Надмірна концентрація відвідувачів на популярних маршрутах призводить до рекреаційної дигресії, ущільнення ґрунтового покриву, розвитку ерозійних процесів та погіршення стану лісів. Мета роботи – встановити вплив рекреації як зовнішнього механічного діяння на ущільнення ґрунту шляхом визначення твердості ґрунту під наметом переважаючих ялинових деревостанів. Для цього вздовж двох туристичних маршрутів пенетрометром виміряно показники твердості ґрунту у межах кореневмісного шару ґрунту на чотирьох дослідних ділянках із різним віддаленням їх від полотна туристичного маршруту. Вцілому під наметом лісового деревостану ґрунтовий покрив не однорідний і отриманим показникам твердості характерна значна мінливість. Встановлено, що для туристичного маршруту «с. Зелене-Угорські скелі» на наближених до полотна стежки (до 20 м) ділянках спостерігається значне збільшення твердості ґрунту порівняно із віддаленими ділянками: на глибині 10 см вдвічі, на глибині 20 см – на 20-40 %, однак із подальшим заглибленням показники твердості вирівнюються. У той же час для популярнішого туристичного маршруту «Еколого-пізнавальна стежка «На гору Піп Іван» на прилеглій безпосередньо до полотна ділянці у верхньому 10-сантиметровому шарі твердість сягає до 19,6 $кг \cdot см^{-2}$, а на глибині 30 см – пікових 37,8 $кг \cdot см^{-2}$ (понад 3 МПа), що є лімітуючими значеннями для кореннаселеності ґрунту ялинових лісів. На полотні туристичних маршрутів спостерігається розвиток інтенсивних ерозійних процесів внаслідок ущільнення ґрунту із зростанням твердості ґрунту понад 60 кг·см-2 (~6 МПа). Практичне значення отриманих результатів та встановлених закономірностей полягає в доповненні існуючих методик оцінки ступеня рекреаційної дигресії у гірських умовах та можуть бути основою для проєктування заходів із врегулювання рекреаційного навантаження і відновлення порушених ділянок

Ключові слова: ущільнення ґрунту; дигресія; туристичний маршрут; пенетрометр; екосистема