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Recreational load as a factor of soil compaction in protected landscapes

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Abstract

Tourism in protected natural areas is growing globally, necessitating environmental monitoring to assess its impact. Recreational monitoring is a systematic approach to regularly assess, analyze, and forecast the state of protected areas affected by recreational activities. Its primary goal is to detect changes caused by anthropogenic pressure in order to ensure sustainable management and conservation of natural resources. This study investigates the effects of recreational pressure on soil properties along the "Volga Switzerland" ecological trail located in the Shcherbakovsky Natural Park (Volgograd Region, Russia) (50.490782, 45.704665). To evaluate soil response to trampling, spatial heterogeneity and varying degradation stages were considered. Soil samples were collected at 12 sites from the trail surface, as well as at distances of 20, 50, and 100 cm from the trail edge. The results indicate a positive correlation between trail intensity and bulk soil density: the more pronounced the trail, the greater the compaction across all depths. For lightly trampled trails, the average density was 1.24 g cm^{-3} (+0.25 g cm^{-3} above background). For moderately trampled trails — 1.46 g cm^{-3} (+0.10 g cm^{-3}), and for heavily trampled trails — 1.51 g cm^{-3} (+0.11 g cm^{-3}). The most significant effects are observed within the trail itself and extend to a depth of 20 cm, particularly under heavily and moderately trampled areas. At a distance of 100 cm, median bulk density values across all depths approach background levels, confirming the localized spatial nature of recreational impact. These findings highlight the importance of soil monitoring in protected areas to maintain their ecological integrity.

Keywords: Bulk density, trail compaction, walking trails, recreational trampling, protected area management.

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Introduction

Recreational activities, including tourism, hiking, and camping, have a significant impact on soils and vegetation in protected natural areas. The main consequences include soil compaction, reduced porosity, impaired aeration and water infiltration, which intensify erosion processes, as well as a decrease in plant species diversity (Liddle, 1975; Kozlowski, 1999; Zhevelev and Sarah, 2008; Jim, 1987; Roovers et al., 2004; Kalahroudi et al., 2023).

Studies on the impact of recreational activities on various soil properties have been conducted at different times in Kazakhstan (Artemyev et al., 2025), Indonesia (Saputra et al., 2024), Finland (Törn et al., 2009) and Spain (Andrés-Abellán et al., 2005). In the United States, the influence of recreational use on fire frequency and vegetation degradation has been examined in natural areas (Young and Gilmore, 1976; Young, 1978; Cole, 1981; Cole and Bayfield, 1993).

Soil compaction occurred because of tourism and other recreational activities. In nature parks of Poland, a relationship was established between increased soil bulk density and the growing number of tourists. This led

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to a decline in soil air and water permeability (Makuch-Pietraś et al., 2017; Shi, 2006). In Roztocze National Park (Poland), studies showed that the intensity of tourist flow caused changes in soil properties, including increased bulk density (Dębicki et al., 2014). In the Carpathian nature parks (Ukraine), the bulk density of topsoil on trails increased by 1.1 to 1.9 times (Lenevych and Mariskevych, 2015; Lenevych et al., 2020). In the Altai region (Russia), the increase ranged from 1.2 to 1.7 times (Elchininova et al., 2023). In the Barnaul ribbon forests (Russia), soil density increased by 0.5 g·cm^{-3} compared to background values (Ershov and Raikhert, 2014). In the Torgashinsky Ridge area (Krasnoyarsk Krai, Russia), high bulk density values were recorded, reaching up to 2.08 g·cm^{-3} (Vorobyeva and Spitsyna, 2019). In the Spring Mountains National Recreation Area (USA), soil density increased significantly – from 1.30 to 1.51 g·cm^{-3} – after 100 hiking passes (Anonymous, 2011). In Turkey (Aladağ Park), the highest compaction was observed after 500 passes (Korkanç, 2014). In China (Baotianman Nature Reserve), trampling increased soil density by 32–65% compared to background values (Shang et al., 2024). In Canada, soil density in campsites rose by 34% (Monti and Mackintosh, 1979). In Japan, a substantial difference in topsoil density was found between trampled (1.08 g/cm^3) and untrampled areas (0.40 g cm^{-3}) (Bhuju and Ohsawa, 1998). In protected natural areas of Spain, the highest density values were recorded on the most frequently visited routes and campsites (1.43 ± 0.07 g·cm^{-3}), picnic areas (1.46 ± 0.104 g·cm^{-3}), near a restaurant (1.48 ± 0.024 g·cm^{-3}), and on the main trail (1.48 ± 0.063 g·cm^{-3}) (Andrés-Abellán et al., 2005).

The impact of recreational activities was not limited to the trails themselves. In Ramat Hanadiv Park (Israel), the effect extended up to 2 meters on each side of the trail (Bar, 2017). In Olenyi Ruchyi Nature Park (Russia), soil compaction was observed at distances of up to 5 meters from recreation areas (Baichibaeva and Sobolev, 2011). A similar pattern was noted in forest parks of Moscow (Russia) (Kuznetsov et al., 2018; Kuznetsov et al., 2019).

In the "Zerkalo Rock" natural monument (Krasnodar Krai, Russia), studies revealed significant compaction in the upper 10-centimeter soil layer compared to undisturbed areas. Within the trail, the soil bulk density reached 1.59 g·cm^{-3}, which was 1.46 times higher than the background value. Tourist activity also affected adjacent zones: at distances of 0.7–1.0 meters from the trail, the bulk density reached 1.33 g·cm^{-3}, exceeding the background value by 1.22 times (Zabolotnyaya et al., 2021). Research by Elchininova near Lake Teletskoye (Altai Mountains, Russia) showed that recreational pressure increased the bulk density of the topsoil layer (0–5 cm) by 1.2–1.7 times compared to the background. This was accompanied by a decrease in soil porosity and deterioration of aeration (Elchininova, 2025).

Soil compaction leads to a reduction in vegetation cover and species diversity. In Ramat Hanadiv Park (Israel), vegetation cover and plant height were significantly lower on trails with high trampling intensity (Bar, 2017). In the Alps, vegetation recovery after trampling took decades (Buckley, 1991). In the forest parks of Moscow, soil compaction was accompanied by a decrease in understory species richness (Kuznetsov et al., 2017). In North Cascades National Park (USA), trampling had long-term effects on the successional development of plant communities (de Gouvenain, 1996). Similar findings were reported for parks in the United Kingdom (Duffey, 1975). Several studies suggest a negative effect of increased soil density on understory growth and development when density exceeds 1.3 g cm^{-3} (Bratton et al., 1966; Bratton et al., 1978; Stohlgren and Parsons, 1986). This was observed in a park in Warsaw (Poland) (Sikorski et al., 2012) and on four pastures in the Cuenca Alta del Río Biosphere Reserve of Manzanares Natural Park (Spain) (Gómez-Limón, de Lucio, 1995).

In addition to compaction, recreational activity also affects other physical and chemical soil properties. Intensive tourism has been shown to reduce soil organic matter content and moisture (Bar, 2017; Yüksek, 2009), impair aeration and water permeability (Makuch-Pietraś et al., 2017; Drewnik et al., 2019; dos Santos Pereira et al., 2022; Li et al., 2022; Ramazanova et al., 2023), and decrease soil microbial diversity (Liu et al., 2023; Shang et al., 2024).

Material and Methods

Study area

Protected areas play a key role in nature conservation and are also of major importance for tourism. International recommendations in the field of conservation have been developed by the International Union for Conservation of Nature (IUCN). However, national protection categories vary between countries. In Russia, nature parks are not directly assigned to IUCN categories, but the system of specially protected natural territories (SPNT) is largely aligned with the international classification. Russian nature parks can be tentatively associated with IUCN Category V — protected landscapes and seascapes. Within these parks, zones are designated for ecological, cultural, or recreational purposes, and respective restrictions and regulations are applied to economic and other activities.

The object of this study was the ecological trail "Volga Switzerland," located in the Shcherbakovsky Nature Park (Volgograd Oblast, Russia) (50.490782, 45.704665). The Shcherbakovskaya meander lies within the Volga Upland. The landforms were shaped by both tectonic activity and exogenous processes such as erosion and deflation. Groundwater is associated with Paleogene and Cretaceous deposits, and occurs at depths of 10 meters or more.

The climate of the study area is warm-summer humid continental (Dfb – Köppen–Geiger classification). It is characterized by strong seasonal contrasts, with cold winters and hot summers. Monthly average temperatures range from –11°C in January to +23°C in July. The mean annual temperature is approximately 6°C. Annual precipitation totals 350–380 mm, with most of it falling during the warm season. Intense summer rainstorms often cause topsoil erosion, leading to gully formation, landslides on steep slopes, and the development of alluvial cones.

The soil cover of Shcherbakovsky Nature Park is diverse due to vertical zonation, geological structure, and hydrogeological conditions. Forested gullies are dominated by Gleysols and Phaeozems, while steppe slopes and interfluves are characterized by Leptosols. Sandy outcrops contain Arenosols and Cambisols. Parent materials include gleyed sandy sediments in depressions, siliceous deposits on slopes, and iron-rich sandy sediments on interfluves, with sandstone bedrock occurring from depths of about 100 cm.

More than one hundred species of herbaceous and woody plants are found in the Shcherbakovskaya meander. On interfluves, common tree species include *Quercus robur* L., *Betula pendula* Roth , *Malus sylvestris* (L.) Mill , *Pyrus communis* L., *and Populus tremula* L. The understory contains *Spiraea hypericifolia* L. , *Euonymus verrucosus* Scop., *Crataegus sanguinea* Pall., *and Chamaecytisus ruthenicus* (Fisch. ex Woł.) Klásk.. Herbaceous associations are dominated by steppe grasses such as *Elytrigia repens* (L.) Desv. ex Nevski , Poa angustifolia *L., Bromus inermis* Leyss., *Artemisia absinthium* L. and *Artemisia vulgaris* L. The upper slope areas are characterized by psammophytic vegetation.

Various forms of tourism are practiced in the park, including educational, scientific, ecological, and recreational tourism. Recreational tourism involves hiking and water-based activities along designated routes, as well as camping in tent sites. Ecotourism is especially well developed. In total, the park offers nine tourist routes, two of which are designated ecological trails.

This study focuses on the ecological trail "Volga Switzerland," located in the central part of the park. The studies were conducted in June 2024.The trail is 1.1 km long and passes through several named sites: "Shcherbakovskaya Gully," "Birch Grove," "Wall of Tears," "Steppe Marmot," "Silent Witnesses of the Past," "Talking Scree," and "Scorpion Hill." The trail is visited by 120 to 400 people annually.

Twelve observation trail were established along the trail to assess the impact of recreational load on soil compaction and vegetation degradation (as measured by projective cover) (Figure 1).

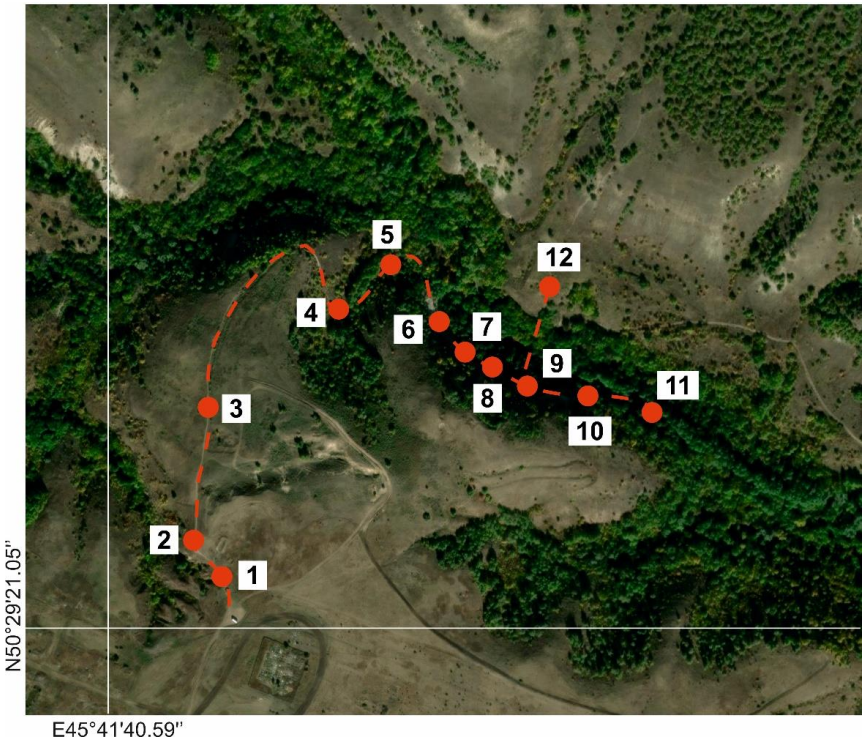


Figure 1. Satellite image of the research object

Vegetation and recreational pressure studies

To evaluate the impact of recreational pressure on soil properties, the spatial heterogeneity of the study trail and different stages of degradation were taken into account. At each of the 12 Trail , soil samples were collected from the trail surface, as well as at distances of 20, 50, and 100 cm from the trail edge.

The degree of trail prominence was evaluated following the classification proposed by Shapochkin (2003). According to this system, trails are assigned to one of three categories – weakly, moderately, or strongly expressed – based on two complementary criteria: trail width and vegetation cover. Weakly expressed trails are narrow, with widths up to 50 cm, and retain relatively high herbaceous vegetation cover, ranging from 10 to 20% of the trail surface. Such trails typically show minimal soil exposure and limited impact on surrounding vegetation. Moderately expressed trails have widths between 50 and 70 cm, and vegetation cover decreases to 5–10%. These trails exhibit more pronounced soil compaction and partial loss of herbaceous species, indicating moderate recreational pressure. Strongly expressed trails are wider than 70 cm and have very low vegetation cover, less than 5%. These trails are heavily impacted, with extensive soil exposure, pronounced compaction, and near-complete removal of original herbaceous vegetation. (Figure 2).



Figure 2. Different degree of trail disturbance. 1 – strong; 2 – medium; 3 – weak

Characteristics of phytocenosis

The description of geobotanical plots was carried out according to the methods of Alekhin (1938) and Ipatov (1998). The methodology includes selecting the location, size, and shape of the vegetation plot. The plots for geobotanical descriptions were established in homogeneous vegetation areas. Square plots of 10 × 10 m were used. The most suitable scheme for plot description is the classical Alekhin–Ipatov scheme, which applies the Drude abundance scale (Drude, 1890).

Sampling points per transect

Within the framework of this study, soil bulk density was investigated at 12 sections of the ecological trail. Among them, 4 sections were characterized by a strong degree of trail expression (degradation), 6 by a moderate degree, and 2 by a weak degree. In total, 60 soil pits were established. At each section, five soil pits were dug: one at a distance of more than 100 cm from the trail (background site), as well as pits directly on the trail and at distances of 20, 50, and 100 cm from it. In total, more than 400 soil samples were collected for the determination of soil bulk density.

Soil properties

The study of soils was carried out using the trench method. The trench crossed the trail and extended 100 cm away from it. Soil samples were taken from the trail itself, as well as at distances of 20, 50, and 100 cm. Soil

classification was performed according to the international soil classification WRB 2022 (IUSS Working Group WRB, 2022). Bulk density was determined separately using the Cylindrical Core Method (undisturbed samples) (cylinder height 5 cm and volume 98.5 cm^{-3}) (Kachinsky. 1958; FAO, 2006). Soil samples were collected at depths of 0–5, 5–10, and 10–20 cm. Since the thickness of the humus horizons often does not exceed 10–15 cm, sampling in the mineral horizons was carried out less frequently (at 10 cm intervals).

Statistical processing of data

Statistical analysis was performed using the XLSTAT statistical software package (Dmitriev, 1995). Descriptive statistics, including minimum, maximum, mean, and standard deviation, were calculated for all variables. The normality of data distribution was assessed using the Jarque–Bera test. Since some datasets did not meet the assumption of normal distribution, differences in soil bulk density among the three trampling intensity levels (strong, moderate, and weak) were evaluated using the non-parametric Kruskal–Wallis test. When significant differences were detected, pairwise comparisons between groups were performed using Dunn's post-hoc test. The significance level was set at $p < 0.05$.

Maps and figures were created using QGIS and CorelDRAW Graphics Suite. A Bing satellite image served as the raster base.

Results

Soil Cover of the "Shcherbakovsky" Nature Park

The soil cover of the Shcherbakovsky Nature Park is notably diverse, influenced by vertical zonation, geological structure, and hydrogeological conditions. In gullies and forested areas, the dominant soil types were Eutric Oxygleyic Chernic Gleysols (Arenic) and Lamellic Bathyleptic Someric Phaeozems (Arenic). On steppe-like slopes and interfluves, the soils included Eutric Hyperskeletic Leptosols (Arenic, Colluvic) and Nudilithic Eutric Hyperskeletic Leptosols (Arenic). Sandy outcrops were mainly occupied by Eutric Arenosols (Areninovic) and Eutric Cambisols (Arenic). A more detailed description of the soil cover of the natural park is presented in previous studies (Gordienko and Andreeva, 2023; Gordienko et al., 2023).

Parent materials also varied. In depressions, soils developed on gleyed sandy sediments and proluvial-deluvial deposits with siliceous fragments. On slopes and steppe areas, the parent materials were thick layers of siliceous (opoka) sediments, with their upper boundary ranging from 20 to 60 cm depending on microrelief. On interfluves, soils formed on iron-rich sandy sediments with clay and pseudo-fibrous inclusions (Lamellic qualifiers). The bedrock appeared from depths of approximately 100 cm, consisting of large blocks of iron-cemented sandstone.

Soil Cover of the Study Trail

Soil profiles were also taken directly on the trails. Their characteristics are shown in Table 1 and Figure 3. The soil cover of the trails varies noticeably depending on changes in relief, hydrological conditions, and anthropogenic impact. Watersheds and slopes (Trails 1–3) are represented by Calcic Someric Kastanozems (Loamic, Densic). These soils are erosion-resistant and rich in calcium. Morphologically, they also show signs of compaction (horizontal aggregate separability). On steep slopes, Eutric Skeletic Leptosols (Clayic, Raptic) are common. These are skeletal, shallow, poorly developed soils prone to erosion. Soils in the valley bottoms are more homogeneous and are mainly Someric Phaeozems with various additional qualifiers (Arenic, Densic, Folic, Solimovic). In areas with high moisture and shallow groundwater Gleyic Phaeozems were observed (Trail 8). On Trails 6 and 9 Someric Phaeozems (Densic, Pyric) were noted, indicating signs of compaction as well as traces of fire in the soil profiles. These trails are located in areas designated for recreation with fire pits.

Statistical Analysis of Soil Bulk Density

To assess the normality of the data, the Jarque–Bera test was applied. Soil density data from the moderately trampled trails followed a normal distribution (J–B = 2.82). However, the dataset from the lightly and heavily trampled trails showed a non-normal distribution (J–B = 17.24 and 8.44, respectively).

The Kruskal–Wallis test revealed significant differences in soil density across trail intensity groups ($\chi^2(2) = 58.74$, $p < 0.001$).

In the background site, which served as a control, the median bulk density values gradually increased with depth: 1.10 g cm^{-3} in the 0–5 cm layer, 1.18 g cm^{-3} in the 5–10 cm layer, and 1.23 g cm^{-3} in the 10–20 cm layer. These values reflect the natural stratification of soil density in undisturbed conditions.

Table 1. Characteristics of Soil and Vegetation Cover of the Studied Trails

Horizon (Depth, cm)	Structure	Texture	Parent material	Phytocoenoses		Projective coverage, %	Trail width, m
				Background	Trail		
Trail 1 – Watershed (Calcic Someric Kastanozems (Loamic, Densic))							
Ah (0-20)	Granular	L	Pale brown carbonate deposits	Herbaceous plants: *Festuca valesiaca* Schleich. ex Gaudin^{+++} *Cichorium intybus* L.$^{++}$ *Carex melanostachya* Bieb. ex Willd^{+++} *Plantago lanceolata* L.$^{+++}$	Herbaceous plants: *Artemisia austriaca* Jacq^{+++} *Artemisia vulgaris* L.$^{++}$	5–66	2.5–2.8
Bk (20-27+)	Blocky						
Trail 2 – Hillslope position (Calcic Someric Kastanozems (Loamic, Densic))							
Ah (0–17)	Granular	L	Pale brown carbonate deposits	Herbaceous plants: *Cichorium intybus* L.$^{++}$ *Carex melanostachya* Bieb. ex Willd^{+++} *Plantago lanceolata* L.$^{+++}$	Herbaceous plants: *Lolium pratense* (Huds.) Darbysh^{+++} *Artemisia austriaca* Jacq^{++} *Thymus pallasianus* Heinr.Braun^{+++} *Stipa capillata* L.$^{++}$	25–30	2
Bk (17–30+)	Blocky						
Trail 3 – Steep slope towards the bottom of the valley (Eutric Skeletic Leptosols (Clayic, Raptic))							
AC (0–5)	Granular	SL	Opoka	Tree layer: *Acer negundo* L., *Betula pendula* Roth Herbaceous plants: *Agrimonia eupatoria* L.$^{++}$ *Dactylis glomerata* L.$^{++}$ *Trifolium repens* L.$^{++}$ *Taraxacum officinale* (L.) Webb ex F.H. Wigg^{++} *Fragaria vesca* L.$^{++}$	Trail: no vegetation	0	0.8
CR (5+)	N/D	N/D					
Trail 4 – Bottom of the valley (Someric Phaeozems (Arenic, Folic))							
Ah (0-10)	Granular	LS	Colluvial material	Tree layer: *Betula pendula* Roth., *Ulmus laevis* Pall., *Acer negundo* L., *Populus nigra* L., *Prunus tomentosa* Thunb., *Crataegus ambigua* C.A. Mey. ex A.K. Becker, *Tilia cordata* Mill., *Populus alba* var. pyramidalis Bunge, *Populus nigra* L.	Herbaceous plants: *Chelidonium majus* L.$^{+++}$ *Phleum pratense* L.$^{++}$ *Oxalis acetosella* L.$^{+++}$ *Arctium lappa* L.$^{++}$ *Lappula squarrosa* (Retz.) Dumort^{+} *Avena fatua* L.$^{+}$ *Equisetum sylvaticum* L.$^{++}$ *Polygonatum odoratum* (Mill.) Druce^{++} *Aegopodium podagraria* L.$^{+++}$ *Anthriscus sylvestris* (L.) Hoffm^{++} Trail: *Avena fatua* L.$^{+}$ *Phleum pratense* L.$^{+}$	25	1.2–1.5
AC (10-22)		S					
C (22–39+)	Rock structure						
Trail 5 – Bottom of the valley (Someric Phaeozems (Arenic, Folic, Solimovic))							
Ah (0–10)	Granular	LS	Colluvial material	Tree layer: *Betula pendula* Roth., *Ulmus laevis* Pall., *Acer negundo* L., *Populus nigra* L., *Prunus tomentosa* Thunb., *Populus alba* var. pyramidalis Bunge, *Populus nigra* L. Herbaceous plants: *Chelidonium majus* L.$^{+++}$ *Phleum pratense* L.$^{++}$ *Oxalis acetosella* L.$^{+++}$ *Urtica dioica* L.$^{+++}$	Herbaceous plants: *Avena fatua* L.$^{+}$ *Phleum pratense* L.$^{+}$	30	0.5–1.0
AC (10–25)		S					
C (25–41+)	Rock structure						

				Arctium lappa L.$^{++}$ *Aegopodium podagraria* L.$^{+++}$ *Anthriscus sylvestris* (L.) Hoffm^{++}			
Trail 6 – Bottom of the valley (Someric Phaeozems (Arenic, Densic, Pyric))							
A (0–7)	Blocky	LS		Tree layer: *Betula pendula* Roth., *Alnus incana* (L.) Moench, *Robinia pseudoacacia* L., *Ulmus laevis* Pall., *Fraxinus excelsior* L., *Amorpha fruticosa* L. Herbaceous plants: *Urtica dioica* L.$^{++}$ *Pilosella officinarum* F.W.Schultz & Sch.Bip.$^{+++}$ *Avena fatua* L.$^{++}$ *Equisetum palustre* L.$^{++}$ *Aegopodium podagraria* L.$^{+++}$ *Glechoma hederacea* L.$^{+++}$	Herbaceous plants: *Aegopodium podagraria* L.$^{++}$ *Urtica dioica* L.$^{+}$ *Glechoma hederacea* L.$^{++}$	50	0.7–1.2
AC (7–20)	Granular	S					
C (20–31+)	Rock structure						
Trail 7 – Bottom of the valley (Someric Phaeozems (Arenic, Densic))							
A (0–12)	Granular	LS	Colluvial mater	Tree layer: no Herbaceous plants: *Plantago major* L.$^{+++}$ *Polygonum aviculare* L.$^{++}$ *Elytrigia repens* (L.) Desv. ex Nevski^{++} *Cichorium intybus* L.$^{+}$ *Trifolium repens* L.$^{++}$ *Taraxacum officinale* (L.) Webb ex F.H.Wigg.$^{+}$	Herbaceous plants: *Cichorium intybus* L.$^{+}$ *Plantago major* L.$^{+}$ *Elytrigia repens* (L.) Desv. ex Nevski^{++}	60	2.0–2.5
AC (12–24)							
C (24–38+)	Rock structure	S					
Trail 8 – Bottom of the valley (Gleyic Leptic Phaeozems (Arenic, Folic, Tonguic))							
A (0–15)	Granular	LS	Colluvial mater	Tree layer: no Herbaceous plants: *Plantago major* L.$^{++}$ *Polygonum aviculare* L.$^{++}$ *Elytrigia repens* (L.) Desv. ex Nevski^{+++} *Cichorium intybus* L.$^{++}$ *Trifolium repens* L.$^{++}$ *Taraxacum officinale* (L.) Webb ex F.H.Wigg.$^{+}$	Herbaceous plants: *Cichorium intybus* L.$^{++}$ *Plantago major* L.$^{++}$ *Elytrigia repens* (L.) Desv. ex Nevski^{++}	60	0.5–1.0
ACg (15–30)							
Cg (30–35+)		S					
Trail 9 – Bottom of the valley (Someric Phaeozems (Arenic, Densic, Pyric))							
A (0–8)	Blocky	LS	Colluvial material	-	Herbaceous plants: *Cichorium intybus* L.$^{+}$ *Plantago major* L.$^{++}$ *Elytrigia repens* (L.) Desv. ex Nevski^{++}	44	There is no trail as such. The entire area is under pressure
AC (8–19)	Granular	S					
C (19–28+)	Rock structure						
Trail 10 – Bottom of the valley (Leptic Someric Phaeozems (Arenic, Folic))							
Ah (0–5)	Granular	LS	Colluvial material	Tree layer: *Alnus glutinosa* (L.) Gaertn., *Ulmus laevis* Pall., *Acer negundo* L., *Populus nigra* L., *Alnus incana* (L.) Moench., *Salix alba* L. Herbaceous plants: *Aegopodium podagraria* L.$^{+++}$ *Aristolochia clematitis* L. $^{++}$ *Lappula squarrosa* (Retz.) Dumort.$^{++}$ *Pseudoroegneria spicata* (Pursh) Á.Löve^{+++} *Convallaria majalis* L.$^{+}$	Herbaceous plants: *Urtica dioica* L.$^{+}$ *Lappula squarrosa* (Retz.) Dumort.$^{++}$	72	0.7–1.2
AC (5–12)	Rock structure	N/D					
C (12–15+)							

				Polygonatum odoratum (Mill.) Druce^{++} *Persicaria hydropiper* (L.) Delarbre^{++} *Ballota nigra* L.$^{++}$			
Trail 11 – Bottom of the valley (Someric Phaeozems (Arenic, Folic))							
Ah (0–7)	Granular	LS	Colluvial material	Tree layer: *Ulmus laevis* Pall., *Acer negundo* L., *Populus nigra* L., *Alnus incana* (L.) Moench., *Salix alba* L., *Rosa canina* L. Herbaceous plants: *Urtica dioica* L.$^{+++}$ *Geranium sylvaticum* L.$^{++}$ *Anthriscus sylvestris* (L.) Hoffm.$^{+++}$ *Chenopodium album* L.$^{++}$ *Butomus umbellatus* L.	Herbaceous plants: Urtica dioica L.$^{+}$ *Lappula squarrosa* (Retz.) Dumort.$^{++}$ *Pseudoroegneria spicata* (Pursh) Á.Löve^{+}	72	0.7–1.2
C (7-18(22))	Rock structure	S					
Ab (22–40+)	Granular	LS					
Trail 12 – Hillslope position (Eutric Hyperskeletic Leptosols (Arenic, Solimovic))							
A (0-28(32))	Granular	SiL	Prolluvial material	Tree layer: no Herbaceous plants: *Silene hellmannii* Claus^{++} *Galium verum* L.$^{+++}$ *Verbascum thapsiforme* Schrad $^{++}$ *Artemisia austriaca* Jacq.$^{++}$ *Dianthus andrzejowskianus*$^{+}$ *Lomelosia* Raf.$^{++}$ *Potentilla argentea* L.$^{+}$ *Sonchus arvensis* L.$^{++}$	-	75	There is no trail as such. The entire area is under pressure
Ah1 (28(32)-95)	Blocky						
Ah2 (95+135+)							

Note: +++ – abundant occurrence (the species occupies approximately 20–50% of the total cover);++ – moderate occurrence (5–20% of the cover); + – low occurrence (less than 5% of the cover); S – sand; LS – loamy sand; SiL – slit loam; L – loam



Figure 3. Example of soils from the studied trails

Discussions

Analysis of vegetation transformation on trails

The study of 12 trails showed that recreational pressure in the park causes a marked simplification of vegetation compared to background communities. Regardless of the original vegetation type (grassland-steppe or forest), trails exhibited reduced species richness and the disappearance of characteristic background species (steppe grasses, forbs, shade-tolerant forest herbs), replaced by ruderal and trampling-resistant species.

Steppe ecosystems (trails 1–2). On watersheds and slopes with Kastanozems, the background vegetation consisted of grassland-steppe communities (*Festuca valesiaca* Schleich. ex Gaudin, *Carex melanostachya* Bieb. ex Willd, *Cichorium intybus* L., *Plantago lanceolata* L.). On trails, these species were replaced by ruderal (*Artemisia austriaca* Jacq, *Artemisia vulgaris* L.) and synanthropic (*Lolium pratense* (Huds.) Darbysh) species. Only some steppe elements persisted (*Stipa capillata* L., *Thymus pallasianus* Heinr.Braun on trail 2). Thus, steppe communities were transformed into ruderal–grass communities with reduced biodiversity.

Forest ecosystems (trails 3–12). In valleys and on slopes, the background vegetation included tree canopies (*Betula pendula* Roth, *Ulmus laevis* Pall., *Acer negundo* L., *Populus nigra* L.) and diverse herbaceous layers (*Chelidonium majus* L., *Oxalis acetosella* L., *Phleum pratense* L., *Arctium lappa* L., *Aegopodium podagraria* L., Urtica dioica L., etc.). Under trampling, forest herbaceous complexes degraded into uniform communities resistant to soil compaction and mechanical disturbance.

Steep slopes with Leptosols (trail 3) were the most vulnerable: vegetation disappeared completely. In valleys (Phaeozems), degradation was evident, but some forest species persisted. On watersheds (Kastanozems), steppe elements remained, but the community transformed into ruderal assemblages.

These changes were closely related to terrain and soil type: less developed and less stable soils (Leptosols, Kastanozems on slopes) experienced deeper degradation; fertile Phaeozems allowed partial preservation of the herb layer but also underwent substantial simplification.

Indicator species on steppe trails included *Artemisia austriaca* Jacq and *Lolium pratense* (Huds.) Darbysh, whereas in forests, key indicators were *Aegopodium podagraria* L., *Urtica dioica* L., *Glechoma hederacea* L., and less frequently *Phleum pratense* L. These species can be considered bioindicators of recreational impact.

Changes in Soil Bulk Density

The analysis demonstrated that increasing recreational load leads to a notable increase in the bulk density of the upper 20 cm of soil.

We examined two aspects of horizontal variability in bulk density: general variability, regardless of distance from the trail; variability based on distance from the trail (20, 50, and 100 cm) (see Figure 4, 5).

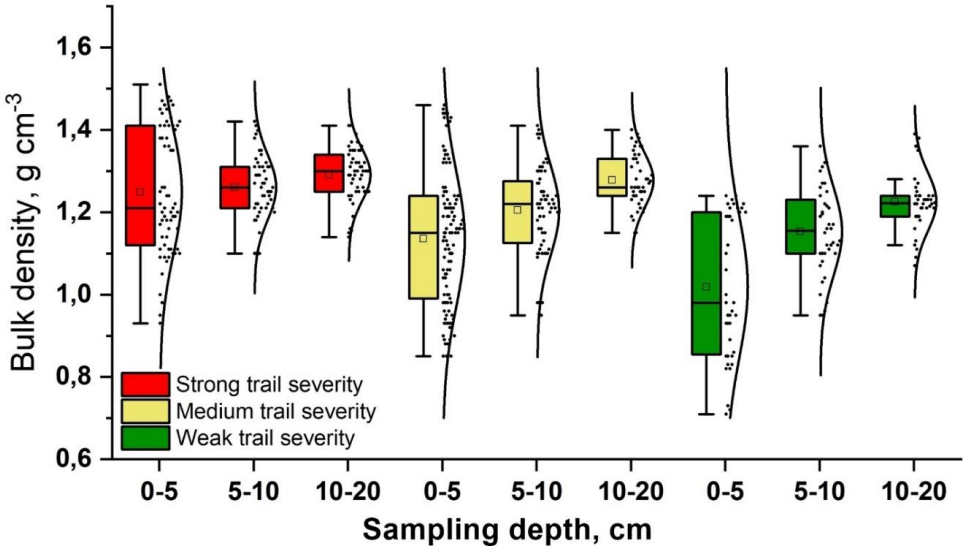


Figure 4. Variation of soil density with depth and depending degree of trail disturbance

In all cases, the highest values were recorded in the surface layer (0–5 cm), regardless of trail intensity or distance from it. For lightly trampled trails, the average density was 1.24 g cm^{-3} (+0.25 g cm^{-3} above background). For moderately trampled trails — 1.46 g cm^{-3} (+0.10 g cm^{-3}), and for heavily trampled trails — 1.51 g cm^{-3} (+0.11 g cm^{-3}).

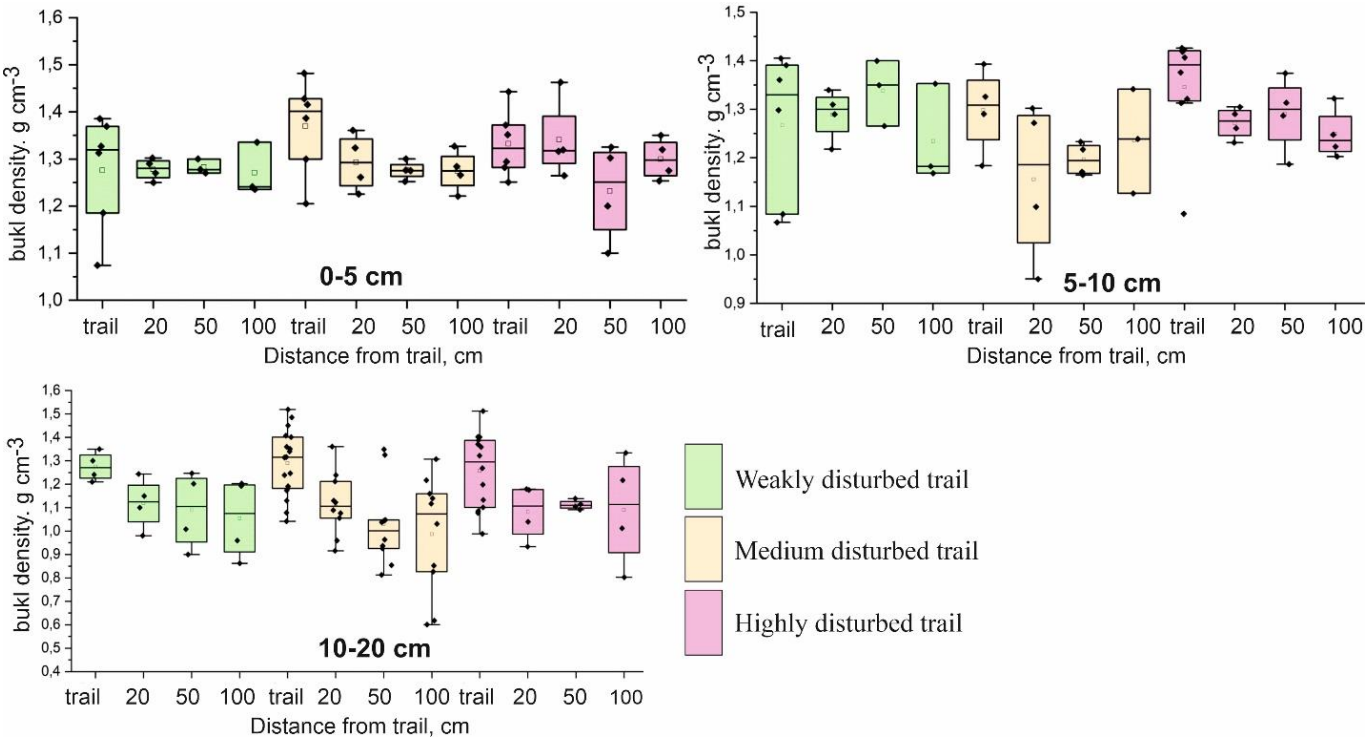


Figure 5. Variation of soil density depending on depth and degree of disturbance and distance from the trail (green box – weakly disturbed trail; yellow – medium; red – highly)

Changes in soil bulk density with depth

Soil bulk density values gradually decreased with depth. However, in the 5–10 cm layer, all trail categories showed the greatest increase relative to background values. Maximum values were recorded at 1.36 g cm^{-3} (+0.23 g cm^{-3}above background) for lightly trampled trails, 1.41 g cm^{-3} (+0.26 g cm^{-3}) for moderately trampled, and 1.42 g/cm^3 (+0.24 g cm^{-3}) for heavily trampled trails.

Although the absolute values in the 5–10 cm layer were lower than in the surface layer (0–5 cm), the increase relative to background was greater. This can be attributed to loosening processes occurring in the uppermost layer. These include the effect of plant root systems, rainfall, and the activity of soil invertebrates. In the 10–20 cm layer, soil density also exceeded background values, although the increase was less pronounced and nearly identical across all trail intensities: 1.39 g cm^{-3} (+0.18 g cm^{-3}) for lightly trampled, 1.40 g cm^{-3} (+0.18 g cm^{-3}) for moderately trampled, and 1.41 g cm^{-3} (+0.18 g cm^{-3}) for heavily trampled trails.

Despite the variation in sampling distances from the trail, the overall dataset revealed a consistent trend of increased soil compaction with depth under recreational pressure.

Spatial variation of soil bulk density near trails

In the surface layer (0–5 cm) directly within the trail area, the median bulk density reached 1.37 g cm^{-3} in heavily trampled trails, significantly exceeding values for moderately (1.23 g cm^{-3}) and lightly (1.22 g cm^{-3}) trampled ones. This indicates substantial soil compaction due to continuous pedestrian pressure. At 10 cm from the trail center, median density values decreased slightly but the pattern remained: 1.32 g cm^{-3} in heavily trampled, 1.25 g cm^{-3}in moderately trampled, and 1.24 g cm^{-3} in lightly trampled trails. Although compaction was reduced, its effects were still observable. At a distance of 20 cm, the trend persisted: 1.29 g cm^{-3} for heavily, 1.26 g cm^{-3} for moderately, and 1.22 g cm^{-3} for lightly trampled trails. This suggests that even at this distance, soil remained affected, although the differences between categories became less pronounced. At 50 cm from the trail edge, a sharp drop in median bulk density was observed: 1.10 g/cm^{-3} in heavily trampled, 0.94 g cm^{-3} in moderately trampled, and 1.00 g cm^{-3} in lightly trampled trails. These values indicate that anthropogenic impact on soil compaction is minimal at this distance.

In the 5–10 cm layer, median bulk density directly within the trail was g cm^{-3} for heavily trampled trails, 1.26 g cm^{-3} for moderately trampled, and 1.21 g/cm^3 for lightly trampled trails. Thus, the degree of trail intensity is positively correlated with soil compaction at this depth. At 20 cm from the trail edge, bulk density decreased: 1.26 g cm^{-3} in heavily trampled trails and 1.21 g cm^{-3} in both moderately and lightly trampled trails. This suggests that compaction effects are still present beyond the trail, though the differences between groups are less pronounced.

In the 10–20 cm layer, differences between trail intensity categories were minimal. Median density within the trail was 1.32 g cm^{-3} (heavily trampled), 1.30 g cm^{-3} (moderately), and 1.24 g cm^{-3} (lightly). Although the influence of recreational pressure was still detectable, it diminished with depth. The slightly higher values under heavily trampled trails reflect long-term anthropogenic impact, while lower values under lightly trampled trails may indicate partial soil recovery. The difference between heavily and moderately trampled trails was minor (0.02 g cm^{-3}). At 20 cm from the trail, medians were 1.29 g cm^{-3} (heavily), 1.26 g cm^{-3} (moderately), and 1.24 g cm^{-3} (lightly trampled). This indicates that the compaction effect extends laterally at depth up to 20 cm from the trail edge. In heavily trampled trails, density remains near trail values, while in lightly trampled trails it approximates background levels. At 50 cm from the trail, group differences nearly disappeared: 1.23 g cm^{-3} (heavily trampled), 1.22 g cm^{-3} (moderately), and 1.24 g cm^{-3} (lightly). This demonstrates that the influence of trampling on the 10–20 cm layer is spatially limited and not detectable beyond 50 cm from the trail.

At a distance of 100 cm from the trail edge, median bulk density values across all layers remain nearly unchanged, approaching background levels. This confirms the spatial limitation of recreational impact.

The results obtained are important for managing recreational activities in protected areas. Severe vegetation degradation and soil compaction observed on steep slopes with shallow soils (Leptosols) indicate the need for strict control of visitor movement and possible zoning restrictions in these areas. In areas of intensive recreational use, measures to reinforce trails, such as gravel covering or the installation of boardwalks, can help reduce soil compaction and vegetation loss. In addition, areas where vegetation has completely disappeared should be considered priority sites for ecological restoration. It should be noted that the results obtained are primarily applicable to steppe and forest-steppe landscapes with Kastanozems, Phaeozem and Leptosols. In other climatic zones and under other soil conditions, the response of vegetation and soils to recreational trampling may differ, so the results should be extrapolated to other landscapes with caution (Li et al., 2024).

Conclusion

Trail intensity is positively correlated with soil bulk density: the more pronounced the trail, the higher the compaction at all depths. The most substantial effects are observed within the trail itself and extend to a depth of 20 cm, particularly under heavily and moderately trampled trails. The contrast between lightly and heavily trampled trails is especially significant — in the 10–20 cm layer, the difference can reach 0.08 g cm^{-3}, indicating deep and persistent structural changes in the soil profile. Maximum compaction occurs in the upper layer (0–5 cm), both directly within the trail and at a lateral distance of up to 20 cm. With increasing depth and distance from the trail, differences in bulk density diminish and become statistically insignificant at 50–100 cm. The coefficient of variation was highest in lightly trampled trails, reflecting greater spatial heterogeneity likely caused by natural variability (e.g., root presence, stones, or moisture differences). In contrast, the lowest variation and standard errors were observed in heavily trampled trails in the upper layers, suggesting consistent and uniform compaction.

The data suggest that tourists often avoid the central part of the trail and instead use its edges, gradually widening paths and exposing vegetation, including vulnerable or protected species, to disturbance and habitat loss. Soil compaction reduces porosity and infiltration capacity, increasing the risk of surface runoff and washout of soil. These findings highlight the broader importance of soil physical responses to trampling under recreational pressure. Indicators such as bulk density, trail width, and vegetation cover provide a basis for evidence-based trail management. Incorporating soil data into recreational planning can help minimize erosion risks, protect biodiversity, and support sustainable use of natural landscapes.

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