Effect of recreation on the spatial variation of soil physical properties

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Abstract. Recreation affects various components of ecosystems. A significant transformation occurs in the soil cover in urban parks. The physical properties of soil are sensitive indicators of the level of anthropogenic transformation, and also allow to assess the state of soil as a habitat for plants and soil animals. The question of quantitative patterns of soil properties variability under the influence of recreation is not solved. There is also little information on the spatial aspect of the variability of soil physical properties in urban ecosystems. The aim of our study is to test the hypothesis that the recreational loads cause the formation of spatial patterns of soil properties, which by their extent greatly exceed the zone of direct influence. The spontaneous walkways within an urban park were investigated as an example of recreational loading. The physical soil properties were measured on a regular grid. The distance to the walkway was treated as a proxy variable that indicates recreational load. The application of multivariate statistical methods allowed to reveal the components of the variation of soil properties of different nature. The effect of recreational load is superimposed on the natural variability of properties. The peculiarity of the influence of recreation consists in sharp increase of soil penetration resistance in the upper soil layers and decrease of this index in the lower layers. The recreational load affects the physical properties of the soil. The soil compaction is the main direction of transformation. This effect gradually attenuates with distance from the source of exposure while occupying a significant portion of the space. The variation of soil properties affects the redistribution of soil moisture and soil air, which significantly affects the living conditions of soil biota.

1. Introduction

Park plantations are an important component of the urban environment that perform a wide range of critical ecological functions \([1–3]\). A significant number of these functions are related to the condition of the soil cover of parks. The recreational load strongly affects the soil \([4–6]\). The compactness of anthropogenic soils is a consequence of technological procedures \([7,8]\). The recreation leads to the development of a network of spontaneous trails. Understanding the effects of human-induced disturbance on ecosystem processes is important for recreational area management \([9]\). The soil penetration resistance is an informative indicator for monitoring soil compaction \([10]\). The physical properties of the soil within these paths are significantly altered \([8]\). Above all, the urban soil is compacted. Human trampling of the soil causes most of the impacts that recreation has on soil and vegetation \([11]\). All soil components (mineral matter, air, water, dead organic matter and living organisms) are disturbed by trampling \([12,13]\). Both
short-term and long-term trampling reduced vegetation cover, plant height and species density, although the long-term impact was more pronounced than the short-term impact. Leaf litter biomass decreases and soil density increases with trampling intensity. Other soil characteristics such as soil moisture, total soil organic matter content and total organic nitrogen content were marginally sensitive to short-term or long-term trampling [14]. Most of the dead organic material in soil is concentrated in the upper layers, especially in the surface layer, which usually consists mainly of organic matter [15]. This layer, called the organic horizon, is crucial to soil health as it plays an important role in the biological activity of the soil [16,17]. The organic horizon also contributes to a good water regime by increasing the absorption capacity of the soil, reducing runoff and increasing moisture retention [18]. Organic horizon is a source of nutrients needed for plant growth and can effectively buffer the underlying mineral soil horizons, which are more vulnerable to compaction [19] and erosion by rainfall [20]. Organic horizons are generally less susceptible to erosion than mineral soil, but if organic matter is crushed by trampling, it can also be eroded, exposing the mineral soil beneath it [21–23]. When trampling compacts the mineral soil, which does not have the physical elasticity of organic matter, the particles are pressed tightly together, dramatically reducing the number of pores between the particles [24–26].

The soil penetration resistance along with other morphological and physical properties is used to diagnose urban soils [4, 27] and is a reliable indicator of recreational load [4, 25]. The soil compaction modifies the soil moisture regime and can inhibit root growth if certain boundary levels are exceeded, resulting in the plant not being able to obtain water or nutrients at depth [28, 29]. The larger pores promote better soil drainage and are usually filled with air can be practically eliminated by trampling [30]. Their elimination can reduce aeration and water availability and make it difficult for plant roots to penetrate the soil. These changes can reduce both the success of germination and the viability of rooted plants and can be detrimental to soil-dwelling organisms [31,32]. The soil penetration resistance was shown to be an important attribute of the ecological niche of mollusks under land reclamation [29,33]. Poor root development makes mature trees more susceptible to windthrow [34]. The soil compaction increases the resistance of the soil to plant root growth [35,36] and impedes the movement of soil animals [37,38], reduces porosity, which slows water transfer and air diffusion, and decreases the rate of mineralization of nutrients [39]. The loss of soil-dwelling biota can lead to further impacts on soil and vegetation, as these organisms are important contributors to soil structure and play an important role in the nutrient cycle. Compacted soils lose much of their infiltration capacity, resulting in increased surface runoff after rainfall or other precipitation [40]. This runoff often leads to increased soil erosion where the soil has been compacted, on trails, in picnic areas, on lookouts and along riverbanks. However, soil compaction is reversed by biotic and frost processes in the soil [41].

2. Research aim and objectives
The main qualitative aspects of the impact of recreational pressure on soil are known, but the quantitative patterns of spatial variability of soil patterns under the influence of trampling are in need to be studied. The aim of our study is to test the hypothesis that the recreational loads cause the formation of spatial patterns of soil properties, which by their extent greatly exceed the zone of direct influence.

3. Material and methods
The study of the influence of recreational load on the physical properties of soil was carried out in Novooleksandrivskiy Park (Melitopol, Ukraine). Two polygons were set up. The soil penetration resistance and soil moisture measurements were carried out in polygon No. 1 in October 2020 and in April 2021. The measurements in polygon No. 2 were taken in April 2020. Each polygon consisted of a network of 105 sampling points located along 7 transects
with 15 sampling points each. Along the transects the sampling points were spaced 3 metres apart. The distance between transects was also 3 meters. The soil moisture in the 0–5 cm layer was measured at each point using a field moisture meter. A hand-held penetrometer was used to measure the soil penetration resistance to a depth of 100 cm at 5 cm intervals (a total of 20 measurements at each point). The soil penetration resistance was measured in the field using the *Eijkelkamp* manual penetrometer, to a depth of 100 cm at 5 cm intervals [8, 42]. The average error of the measurement results of the device is ±8%. Measurements were made with a cone with a cross section of 1 cm². At each measurement point, the soil penetration resistance was performed in only one replication. The location of trees within the polygon and in the 3 meters vicinity was also mapped. The location of spontaneous pathways was mapped. Based on the results, a geographical information database was created in the software ArcGIS (ESRI). Descriptive statistics have been calculated in the software STATISTICA (Statsoft).

4. Results

The polygons 1 and 2 differed in the level of recreational load, which was characterised by the distances from the spontaneous walkways. The distance from the pathways within the polygon 1 was 3.1±0.24 m (maximum distance was 9.4 m). The distance from the pathways within the polygon 2 was 4.1±0.32 m (maximum distance was 14.9 m). The differences were statistically significant (*t*-value was –3.08, *p*=0.002). The distance to trees within the polygon 1 was 3.2±0.19 m (maximum distance was 10.0 m). The distance to trees within the polygon 2 was 2.5±0.15 m (maximum distance was 7.6 m). The differences were statistically significant (*t*-value was 2.28, *p*= 0.022). There was a statistically significant correlation (*r* = –0.36, *p* < 0.001) between distance to pathways and trees.

The soil moisture within the polygon No. 1 in October 2020 was 15.53±0.1% and was in the range of 12.8–18.50% in 95% of the cases (table 1). The distribution of this parameter was symmetrical and without kurtosis. The soil penetration resistance was the lowest at the depth of 0–5 cm, where it was 3.01±0.08 MPa. With increasing soil depth this index increased sharply up to the depth of 35–40 cm, where the soil penetration resistance reached its maximum of 8.66±0.08 MPa. With further increase in depth the soil penetration resistance decreased slightly and reached a plateau. The asymmetry of distribution was positive in soil layers 0–20 cm, while in deeper layers the asymmetry was negative. This indicates that the distribution of the soil penetration resistance in the upper soil layers was shifted to the left, so that the median was less than the mean value of the index. In deeper soil layers the distribution was shifted to the right, so the median was greater than the mean. The kurtosis was statistically significantly different from the random alternative in layers 5–25 cm. The kurtosis indicated that values close to the modal were more frequent than the random distribution would suggest.

The soil moisture within the polygon No. 1 in April 2021 was 24.19±0.32% and was in the range of 18.0–32.0% in 95% of cases (table 2). The distribution of this index was symmetrical and without kurtosis. The soil penetration resistance was the lowest at the depth of 0–5 cm, where it was 1.44±0.04 MPa. With increasing depth, this index increased sharply up to a depth of 95–100 cm, where the soil penetration resistance reached its maximum of 3.75±0.06 MPa. The local maxima of the soil penetration resistance were at depths of 15–25 and 75–80 cm. The asymmetry maximum was found at a depth of 25–30 cm, which indicated a shift of asymmetry to the left. This feature explains why the median of the soil penetration resistance in this soil layer was smaller than the mean value. The distribution of the soil penetration resistance in the profile either had no kurtosis or the kurtosis was negative, indicating that the observed values tended towards the modal level. The distribution was bimodal at a depth of 25–30 cm.

The soil moisture within the polygon No. 2 in April 2021 was 26.44±0.26% and was in the range of 22.0–32.1% in 95% of cases (table 3). The distribution of this index was symmetrical and without kurtosis. The moisture content in the polygon No. 1 was lower than in polygon
Table 1. Descriptive statistics of soil moisture and penetration resistance variability at different depths within polygon 1 (2020, October) \((N = 105)\).

| Soil layer, cm | Mean±st.error | Median | Percentile | Skewness±st.error | Kurtosis±st.error |
|----------------|---------------|--------|------------|-------------------|------------------|
|                |               | 2.5%   | 97.5%      |                   |                  |
| Soil moisture, %| 0–5           | 15.53±0.11 | 15.60 | 12.80 | 18.50 | –0.02±0.22 | 0.69±0.43 |
| Soil penetration resistance, MPa | 0–5           | 3.01±0.08 | 2.80 | 1.80 | 5.20 | 0.89±0.22 | 0.02±0.43 |
| 5–10           | 4.73±0.12 | 4.47 | 2.80 | 7.50 | 0.66±0.22 | –0.49±0.43 |
| 10–15          | 6.09±0.14 | 6.00 | 3.60 | 9.15 | 0.39±0.22 | –0.67±0.43 |
| 15–20          | 6.95±0.13 | 6.80 | 4.60 | 9.70 | 0.18±0.22 | –0.92±0.43 |
| 20–25          | 7.63±0.12 | 8.00 | 5.00 | 9.80 | –0.37±0.22 | –0.76±0.43 |
| 25–30          | 8.19±0.11 | 8.36 | 6.00 | 9.80 | –0.60±0.22 | –0.34±0.43 |
| 30–35          | 8.35±0.08 | 8.42 | 6.00 | 9.78 | –0.62±0.22 | 0.03±0.43 |
| 35–40          | 8.66±0.08 | 8.73 | 6.55 | 10.27 | –0.62±0.22 | 0.34±0.43 |
| 40–45          | 8.48±0.09 | 8.62 | 6.20 | 9.83 | –0.76±0.22 | 0.01±0.43 |
| 45–50          | 8.17±0.09 | 8.29 | 6.00 | 9.40 | –0.76±0.22 | 0.05±0.43 |
| 50–55          | 7.95±0.05 | 8.05 | 6.66 | 8.75 | –0.70±0.22 | –0.17±0.43 |
| 55–60          | 7.96±0.05 | 8.06 | 6.66 | 8.80 | –0.56±0.22 | –0.45±0.43 |
| 60–65          | 7.96±0.05 | 8.08 | 6.86 | 8.77 | –0.55±0.22 | –0.49±0.43 |
| 65–70          | 7.96±0.05 | 8.06 | 6.78 | 8.81 | –0.60±0.22 | –0.35±0.43 |
| 70–75          | 7.96±0.05 | 8.07 | 6.76 | 8.71 | –0.61±0.22 | –0.22±0.43 |
| 75–80          | 7.96±0.05 | 8.10 | 6.72 | 8.71 | –0.69±0.22 | –0.18±0.43 |
| 80–85          | 7.96±0.05 | 8.09 | 6.67 | 8.71 | –0.66±0.22 | –0.11±0.43 |
| 85–90          | 7.97±0.05 | 8.10 | 6.62 | 8.70 | –0.68±0.22 | –0.12±0.43 |
| 90–95          | 7.95±0.05 | 8.07 | 6.73 | 8.67 | –0.74±0.22 | 0.12±0.43 |
| 95–100         | 7.95±0.05 | 8.07 | 6.75 | 8.68 | –0.73±0.22 | 0.12±0.43 |

No. 2 \((t = 6.61, p < 0.001)\). The soil penetration resistance was lowest at a depth of 0–5 cm, where it had a value of 1.18±0.03 MPa. With increasing depth, this index increased sharply up to a depth of 95–100 cm, where the soil penetration resistance reached its maximum of 4.54±0.07 MPa. The local maximums of the soil penetration resistance were at depths of 15–25 and 75–80 cm. A general decreasing trend along the profile was detected for the asymmetry index. The highest level of asymmetry was found for the upper soil layers 0–25 cm, indicating a leftward shift in distribution. The two local minima of soil penetration resistance were found: at a depth of 30–35 and 80–90 cm. At these depths the asymmetry was not statistically significantly different from zero, indicating a symmetrical distribution. The kurtosis also had a decreasing trend with depth. The local minimum of kurtosis was at a depth of 55–90 cm, indicating the bimodal nature of the distribution.

The soil penetration resistance was greater the lower the soil moisture content (figure 1). After log-transformation the dependence had a linear character.

A General Linear Model with moisture and distance from walkways and trees as predictors was able to explain 74–94% of the variation in the soil penetration resistance (Table 1). The regression coefficients indicated that the soil penetration resistance decreased with increasing moisture content. The dependence of the soil penetration resistance on the distance to the walkways and trees was non-linear and statistically significantly described by a second-degree
Table 2. Descriptive statistics of soil moisture and penetration resistance variability at different depths within polygon 1 (2021, April) ($N = 105$).

| Soil layer, cm | Mean±st.error | Median | 2.5%  | 97.5% | Skewness±st.error | Kurtosis±st.error |
|----------------|---------------|--------|-------|-------|-------------------|------------------|
| 0–5            | 24.19±0.32    | 1.50   | 0.75  | 2.45  | 0.21±0.24         | -0.76±0.47       |
| 5–10           | 1.44±0.04     | 1.90   | 0.90  | 2.90  | 0.00±0.24         | -0.50±0.47       |
| 10–15          | 2.23±0.06     | 2.20   | 1.00  | 3.50  | 0.28±0.24         | -0.65±0.47       |
| 15–20          | 2.54±0.08     | 2.50   | 1.20  | 4.10  | 0.14±0.24         | 0.07±0.47        |
| 20–25          | 2.56±0.05     | 2.50   | 1.70  | 3.67  | 0.27±0.24         | -0.61±0.47       |
| 25–30          | 2.59±0.06     | 2.50   | 1.65  | 4.30  | 0.74±0.24         | 0.85±0.47        |
| 30–35          | 2.70±0.06     | 2.70   | 1.60  | 4.00  | 0.18±0.24         | -0.36±0.47       |
| 35–40          | 2.80±0.06     | 2.77   | 1.70  | 4.00  | 0.06±0.24         | -0.61±0.47       |
| 40–45          | 2.91±0.06     | 2.90   | 1.90  | 4.10  | 0.26±0.24         | -0.62±0.47       |
| 45–50          | 3.05±0.06     | 3.00   | 2.00  | 4.40  | 0.33±0.24         | -0.40±0.47       |
| 50–55          | 3.28±0.07     | 3.10   | 2.25  | 4.53  | 0.16±0.24         | -0.78±0.47       |
| 55–60          | 3.39±0.07     | 3.30   | 2.20  | 4.50  | 0.18±0.24         | -0.85±0.47       |
| 60–65          | 3.50±0.07     | 3.40   | 2.30  | 4.80  | 0.24±0.24         | -0.61±0.47       |
| 65–70          | 3.54±0.07     | 3.60   | 2.30  | 5.00  | 0.22±0.24         | -0.49±0.47       |
| 70–75          | 3.54±0.07     | 3.60   | 2.30  | 4.80  | 0.15±0.24         | -0.17±0.47       |
| 75–80          | 3.62±0.07     | 3.50   | 2.30  | 5.00  | 0.33±0.24         | 0.18±0.47        |
| 80–85          | 3.70±0.07     | 3.70   | 2.00  | 5.15  | 0.10±0.24         | 0.09±0.47        |
| 85–90          | 3.69±0.08     | 3.60   | 2.30  | 5.30  | 0.25±0.24         | -0.52±0.47       |
| 90–95          | 3.75±0.06     | 3.70   | 2.60  | 5.00  | 0.19±0.24         | -0.20±0.47       |
| 95–100         | 3.75±0.06     | 3.70   | 2.60  | 5.00  | 0.16±0.24         | -0.27±0.47       |

Figure 1. Dependence of soil penetration resistance in 0–5 cm layer (a) and 5–10 cm layer (b) (ordinate axis, MPa, log-transformed data) on soil moisture (abscissa axis, %, log-transformed data).

The calculation made it possible to find the distances at which the soil penetration resistance reached a local minimum.
Table 3. Descriptive statistics of soil moisture and penetration resistance variability at different depths within polygon 2 (2021, April) (*N* = 105).

| Soil layer, cm | Mean±st.error | Median | Percentile 2.5% | Percentile 97.5% | Skewness±st.error | Kurtosis±st.error |
|---------------|---------------|--------|-----------------|------------------|------------------|------------------|
| Soil moisture, % | 0–5          | 26.44±0.26 | 26.40          | 22.00           | 32.10            | 0.21±0.24        | -0.19±0.47       |
| Soil penetration resistance, MPa | 0–5          | 1.18±0.03   | 1.15           | 0.70            | 2.00             | 0.79±0.24        | 0.38±0.47        |
|               | 5–10         | 1.50±0.04   | 1.50           | 0.90            | 2.50             | 0.46±0.24        | 0.04±0.47        |
|               | 10–15        | 1.88±0.05   | 1.90           | 1.10            | 2.80             | 0.38±0.24        | -0.60±0.47       |
|               | 15–20        | 2.31±0.06   | 2.20           | 1.40            | 4.00             | 0.71±0.24        | 0.70±0.47        |
|               | 20–25        | 2.68±0.05   | 2.64           | 1.70            | 3.90             | 0.29±0.24        | -0.03±0.47       |
|               | 25–30        | 2.86±0.06   | 2.70           | 1.62            | 4.00             | 0.17±0.24        | -0.22±0.47       |
|               | 30–35        | 2.86±0.06   | 2.90           | 1.50            | 3.93             | -0.11±0.24       | -0.25±0.47       |
|               | 35–40        | 3.18±0.07   | 3.10           | 2.10            | 5.10             | 0.55±0.24        | -0.41±0.47       |
|               | 40–45        | 3.46±0.08   | 3.40           | 2.00            | 5.20             | 0.43±0.24        | -0.28±0.47       |
|               | 45–50        | 3.68±0.09   | 3.60           | 2.00            | 5.31             | 0.21±0.24        | -0.77±0.47       |
|               | 50–55        | 3.73±0.09   | 3.57           | 2.10            | 5.41             | 0.38±0.24        | -0.78±0.47       |
|               | 55–60        | 3.88±0.09   | 3.70           | 2.40            | 5.63             | 0.27±0.24        | -0.77±0.47       |
|               | 60–65        | 4.03±0.09   | 3.80           | 2.50            | 5.63             | 0.33±0.24        | -1.03±0.47       |
|               | 65–70        | 4.19±0.09   | 4.00           | 2.50            | 5.86             | 0.12±0.24        | -1.02±0.47       |
|               | 70–75        | 4.37±0.09   | 4.20           | 2.50            | 5.98             | -0.02±0.24       | -0.73±0.47       |
|               | 75–80        | 4.44±0.10   | 4.30           | 2.60            | 6.09             | -0.03±0.24       | -0.95±0.47       |
|               | 80–85        | 4.54±0.07   | 4.49           | 3.20            | 6.09             | 0.31±0.24        | -0.30±0.47       |
|               | 85–90        | 4.54±0.07   | 4.49           | 3.20            | 6.09             | 0.34±0.24        | -0.31±0.47       |
|               | 90–95        | 4.54±0.07   | 4.49           | 3.20            | 6.09             | 0.36±0.24        | -0.31±0.47       |
|               | 95–100       | 4.54±0.07   | 4.49           | 3.20            | 6.09             | 0.38±0.24        | -0.31±0.47       |

The local minimum was observed at a distance of 3.0–3.9 meters from the recreational paths. At depths of 0–5 and 50–55 cm, a significant increase in this index was observed to 4.7 and 5.3 meters respectively.

Thus, an increase in the soil penetration resistance indices was observed both near the recreational paths and at a considerable distance from them. A minimum value of the soil penetration resistance was observed at a distance of 3–5 meters from the recreational paths. A similar pattern was observed with regard to the effect of distance from trees on the soil penetration resistance. The soil penetration resistance was greatest near the trees and at a considerable distance from the trees. A local minimum of the soil penetration resistance was observed at 1.1–7.7 meters. At a depth of 30 to 60 cm a local minimum of the soil penetration resistance was observed at a distance of 6.3–7.8 meters from the trees. At a depth of 60–95 cm a local minimum of the soil penetration resistance was observed at a distance of 1.1–2.2 meters from the trees.

5. Discussion
Soil penetration resistance measured with a cone penetrometer is an important parameter in many soil management studies [43,44]. The level of soil penetration resistance depends on many factors. The penetration resistance is a physical property of soil that depends on soil texture
between spring and autumn, as there is an inverse relationship between the soil moisture content in the soil [13, 64]. These processes explain the differences in soil penetration resistance at the distance from the paths or trees, calculated on the basis of a quadratic model (statistically significant beta regression coefficients for $p < 0.05$ are shown).

| Layer | $R^2_{adj}$ | Wetness | $\log_{10}\text{Trail}$ | $\log_{10}\text{Trail}^2$ | $\log_{10}\text{Tree}$ | $\log_{10}\text{Tree}^2$ | Extremum distance, m |
|-------|-------------|---------|----------------|----------------|----------------|----------------|-------------------|
| 0-5   | 0.74        | -0.25±0.06 | -0.51±0.10 | 0.38±0.10 | -0.97±0.11 | 0.73±0.11 | 4.7 |
| 5-10  | 0.82        | -0.15±0.05 | -0.51±0.09 | 0.47±0.09 | -0.71±0.09 | 0.49±0.10 | 3.5 |
| 10-15 | 0.85        | -0.17±0.05 | -0.42±0.08 | 0.38±0.08 | -0.66±0.09 | 0.47±0.09 | 3.5 |
| 15-20 | 0.85        | -0.16±0.05 | -0.32±0.08 | 0.28±0.08 | -0.43±0.09 | 0.26±0.09 | 3.8 |
| 20-25 | 0.90        | -0.15±0.04 | -0.29±0.07 | 0.27±0.07 | -0.19±0.07 | 0.05±0.07 | 3.4 |
| 25-30 | 0.92        | -0.12±0.04 | -0.19±0.06 | 0.19±0.06 | -0.19±0.06 | 0.08±0.06 | 3.3 |
| 30-35 | 0.94        | -0.11±0.03 | -0.16±0.05 | 0.15±0.05 | -0.17±0.05 | 0.10±0.05 | 3.4 |
| 35-40 | 0.94        | -0.08±0.03 | -0.12±0.05 | 0.12±0.05 | -0.15±0.05 | 0.09±0.05 | 3.0 |
| 40-45 | 0.93        | -0.08±0.03 | -0.12±0.06 | 0.11±0.06 | -0.12±0.06 | 0.08±0.06 | 3.4 |
| 45-50 | 0.90        | -0.06±0.04 | -0.07±0.06 | 0.06±0.06 | -0.10±0.07 | 0.09±0.07 | 3.6 |
| 50-55 | 0.91        | -0.06±0.04 | -0.04±0.06 | 0.03±0.06 | -0.03±0.07 | -0.01±0.07 | 5.3 |
| 55-60 | 0.90        | -0.12±0.04 | -0.08±0.06 | 0.06±0.06 | 0.01±0.07 | -0.05±0.07 | 3.9 |
| 60-65 | 0.90        | -0.09±0.04 | -0.21±0.06 | 0.19±0.06 | 0.03±0.07 | -0.08±0.07 | 3.5 |
| 65-70 | 0.89        | -0.08±0.04 | -0.10±0.07 | 0.10±0.07 | 0.01±0.07 | -0.05±0.07 | 3.3 |
| 70-75 | 0.89        | -0.08±0.04 | -0.11±0.07 | 0.11±0.07 | 0.02±0.07 | -0.04±0.07 | 3.4 |
| 75-80 | 0.88        | -0.06±0.04 | -0.13±0.07 | 0.12±0.07 | -0.01±0.08 | -0.03±0.08 | 3.5 |
| 80-85 | 0.87        | -0.05±0.04 | -0.10±0.07 | 0.09±0.07 | -0.04±0.08 | -0.01±0.08 | 3.5 |
| 85-90 | 0.86        | -0.07±0.05 | -0.16±0.08 | 0.15±0.08 | -0.08±0.08 | 0.04±0.08 | 3.4 |
| 90-95 | 0.91        | -0.07±0.04 | -0.18±0.06 | 0.17±0.06 | -0.15±0.07 | 0.10±0.07 | 3.3 |
| 95-100| 0.91        | -0.08±0.04 | -0.17±0.06 | 0.16±0.06 | -0.15±0.07 | 0.11±0.07 | 3.4 |

Table 4. The regression coefficients obtained from GLM analysis of the dependence of the soil penetration resistance on the soil moisture and the distance from the recreational paths and trees. The extreme distances indicate the distance at which there is a minimum value of the soil penetration resistance at the distance from the paths or trees, calculated on the basis of a quadratic model (statistically significant beta regression coefficients for $p < 0.05$ are shown).

and bulk density [45, 46], moisture content [47, 48], porosity and permeability [49], particle size distribution [50], structure, mineral and organic matter content of soil [51, 52], pH, cation exchange capacity, clay particle thickness, presence of iron oxides and free aluminum hydroxide, which determine the nature of the resulting cohesive forces between soil constituent [53]. Soil penetration resistance is highly dependent on soil type and soil properties such as volumetric water content, soil matrix potential, bulk density, porosity and organic matter content [54]. The temporal and spatial dynamics of the soil moisture content are a significant cause that affects this indicator. To reduce the influence of water content on measured values, the measurement of soil penetration resistance data at soil water content close to field capacity was proposed [55], or to correct data obtained at different water content to a reference soil penetration resistance at field capacity [56–58]. The differences in observed soil penetration resistance values with varying water content and bulk density of different soils were attributed mainly to the influence of soil texture, organic matter and soil water retention curve [44, 50, 59–62]. In spring after snowmelt and relatively low intensity of evaporation of moisture from the soil surface, the soil moisture content is significantly higher than in autumn [33, 63]. The low precipitation in late summer and early spring, which is superimposed on the considerable intensity of moisture evaporation from the soil surface during the warm season, leads to a drastic reduction of its reserves in the soil [13, 64]. These processes explain the differences in soil penetration resistance between spring and autumn, as there is an inverse relationship between the soil moisture content.
and its penetration resistance. The differences in soil moisture can also be induced by the recreational load. An increase in recreational load leads to an increase in the soil compactness, the consequence of which may be a reduction in the volume of the soil pore space and thus a reduction in the volume available for the storage of water. Also, an increase in compactness leads to an increase in the proportion of small pores, which increases the intensity of capillary uplift of the water and thus contributes to an increase in the rate of evaporation of water from the soil surface.

The recreation can have not only a direct effect on soil moisture variation, but also an indirect one [65,66]. Recreational impacts can lead to changes in the microrelief of an area, which affects the redistribution of moisture. Pathways lead to a higher density of soil, resulting in a localised lowering of the topography [67]. Therefore a berm is formed along the paths and water can run off along it. Also in pathways the aggregate structure is lost and consequently cracks form in them into which moisture can escape in case of precipitation.

There is a significant increase in the soil penetration resistance in the vicinity of the trails and on the trails themselves [5]. The mechanism for this phenomenon is quite obvious. The systematic movement of large numbers of people leads to an increase in the soil compaction, which is reflected in the soil penetration resistance. Evidence was obtained which indicated that human trampling had the greatest effect on overall porosity and soil penetration resistance [11]. The soil penetration resistance in the topsoil increased significantly after 200 and 500 passes compared to the control plots. The soil penetration resistance, which was 3.78 MPa in the topsoil of the control plots, reached 6.06 MPa after 500 passes. The total topsoil porosity after 500 passes was significantly different from the control plots. While the total porosity was 52.38% in the topsoil of the control plots, it decreased to 41.41% after 500 passes. Other soil properties were generally unchanged in the short term. The relative vegetation cover and relative vegetation height also decreased significantly after trampling. Relative vegetation cover, which decreased to 84% after 25 passes, decreased to 67% after 500 passes. Relative vegetation height was 69% after 25 passes and decreased to 27% after 500 passes. A significant reduction in total vegetation cover was observed after 200 and 500 passes. Compared to the control strip, vegetation height was significantly different after 25, 75, 200 and 500 passes [11].

Our results suggest that the compaction effect is observed over a much larger spatial range than the visible boundaries of trails. A soil compaction effect is observed at a distance of 3-5.3 metres from the trails. This effect is largely reflected in the compaction of the surface soil layer, but the soil penetration resistance of the soil is also sensitive to this compaction over the entire measured depth range. In addition, the compaction at a depth of 55–60 cm extends to a distance of up to 5 meters. Thus, the area of recreational influence exceeds the area of the visible network of spontaneous trails by a factor of 5–10.

The trees in the park plantation also have a non-linear effect on the soil penetration resistance. Plants affect the compactness of the soil [7, 69]. Tree stands in a riparian mixed forest are a significant factor structuring both the herbaceous community and the spatial variation of soil physical properties [70–72]. The roots transmit the weight of the trees into the soil, compacting it [73,74]. As roots expand, they penetrate through the soil and modify the physical, chemical, and biological properties in the surrounding area, the rhizosphere [75, 76]. These changes can persist after root degradation, forming a branched system of associated biopores [77]. Natural disturbances such as geological events, glacial activity, or soil sliding can change the degree of the soil compaction on a large scale [19,78]. Alternating wetting and drying can compact the soil as a result of swelling and shrinkage processes [79]. The soil near the tree trunks has greater penetration resistance. The oscillatory movements of the crown under the action of wind energy are transmitted through the trunk to the soil. The vibrational energy is transmitted to the soil and is spent on its compaction, which makes the soil near the trunks more compact. The trees also actively evaporate moisture, so the soil penetration resistance can be higher in the vicinity
of the tree trunks. The effect of trees on the soil compactness extends over a distance of up to 8 meters. The greatest attenuation distance for the effect of trees is observed at a depth of 20–60 cm, which corresponds to the depth of the most dense root system of tree plants. The attenuation of oscillatory movements that are transmitted to the root system may be the cause of this local maximum. The second local impact peak is associated with the greatest measured depth and it cannot be ruled out that it is wiped out to a greater depth. Along with the attenuation of oscillatory movements, it can be assumed that a reduction in water content due to its intensive consumption by the roots of the tree plants may be the cause of the observed impact on the soil penetration resistance.

6. Conclusion
The arrangement of trees forms patterns that are similar to the mechanisms of variability in soil penetration resistance in natural conditions. The influence of spontaneous pathways on the spatial heterogeneity of soil properties is commensurate with the natural variability in magnitude. The superposition of these two sources of variation in the soil properties creates a mosaic of parkland soil cover. The effect of recreational pathways has considerable spatial extent, both horizontally and vertically. The boundaries of this effect extend considerably beyond the visible boundaries of the pathways. The findings point to the need for recreational space management to minimise the negative effect of spontaneous paths, the role of which has apparently been previously underestimated.

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