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The influence of anthropogenic trampling of gray forest soils on their physical properties

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Abstract

The purpose of the study was to determine quantitative and relative indicators that significantly affect the physical properties of gray forest soils within the park ecological trail, to show changes in the compacted soil during natural recovery. Physical properties were determined in 3-fold repetition with the help of three-dimensional cylinders, followed by the calculation of their density and porosity. Population of physiologically active roots of the upper 0.5-meter layer of gray forest soils was determined by the monolith method in 5-fold repetition. It was found out that under the influence of anthropogenic trampling, the greatest degradation changes of the studied physical indicators are manifested in the upper 10-centimeter layer of gray forest soils. An increase in the density by 32.1–38.0% and solids content of the soil by 14.1–22.8%, as well as a decrease in the volume of pores by 32.0–44.3% was recorded and mass of physiologically active roots of woody plants by 84.6–91.2%. The natural restoration of soil occurs most intensively in the upper 5-cm layer. At the same time, over a 15-year period, the following changes were observed – a decrease in density by 19.5%, the content of solid particles by 9.9%, an increase in the content of pores by 39.1% and physiologically active roots woody plants by 330.0%. Quantitative and relative indicators of their physical properties obtained for anthropogenically compacted gray forest soils explain the changes in the mass of physiologically active roots of deciduous woody plants that grow in the centers with anthropogenically compacted soils.

Key words: eco-trail; park plantings; above ground cover; soil density; physiologically active roots

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1. Introduction

Anthropogenic trampling of soils, which is currently quite intensively manifested within urban park phytocenosis, belongs to the destructive factors that usually cause significant, and under a certain combination of circumstances, irreversible changes in them (Pescott & Stewart 2014; Kutiel 2017; Lenevych et al. 2021). At the same time, the negative consequences of trampling the soil surface, first of all, are manifested due to the deterioration of the performance of ecological functions by green plantings (Bernhardt-Romermann et al. 2011; Orlov et al. 2021), as well as in the strengthening of the manifestation of the consequences of erosion processes (Lavrov et al. 2014; Selesa & Cerda 2020; Nir et al. 2022), reduction of the humus content in the soil (Henyk et al. 2014; Nir et al. 2022) and a decrease in the number of certain species of biota in their communities (Ayres et al. 2008; Malmivaara-Lamsa 2008; Kissling et al. 2009). In general, soil compaction, as a result of their trampling, causes functional changes in edaphotopes (Cole 2004; Cakir et al. 2010; Henyk et al. 2014; Lenevych et al. 2021; Orlov et al. 2021), affects the quantitative and relative indicators of the species composition of the above-ground vegetation cover (Cole 2004; Roovers et al. 2004; Kissling et al. 2009; Henyk & Dyda 2013; Korkanç 2013; Li et al. 2020). That can be reflected in the microclimatic indicators of the surrounding areas (Lenevych et

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al. 2021). The beginning of digressive changes occurring in phytocenosis as a result of trampling is usually visually identified by the degree of damage (degradation) of the above-ground plant cover (Ryzhov & Brovko 2012; Korkanç 2013). In the case of excessive soil compaction, its effect is quite clearly manifested within the boundaries of paths, platforms and other recreational facilities and as well can be assessed by the degree of degradation of above-ground grass cover on them (Kissling et al. 2009; Lenevych et al. 2021).

The impact of anthropogenic trampling on the state of the soil, as well as the productivity of phytocenosis within park landscapes, has become the subject of study by both scientists and specialists, who take care of the maintenance and preservation of green spaces for various purposes, starting from the second half of the 20th century.

During this period, the following was found out. Excessive soil compaction causes significant changes in the morphological and physical properties of soils. In particular, there is a change in the porosity of soils, their water-physical properties and temperature regime deteriorate, which negatively affects the regime of plant nutrition (Ryzhov et al. 2013). For sandy soils, it was established that their optimal density (volumetric mass) is 1.20–1.45 g m^{-3}. At the same time, if their density is less than 1.20 g m^{-3}, such soil is unable to retain moisture, and plants suffer from its lack, and if it is greater than 1.60 g m^{-3}, they are unable to develop roots. In sandy soils, the upper 3–10 cm layer is usually compacted (Ryzhov et al. 2013), and in the centers of excessive compaction, changes in physical parameters can be traced to a depth of 50 cm, which negatively affects growth and functioning of root systems in woody plants (Ryzhov et al. 2014).

For the gray forest soils common within the forests of the Oleksandria dendrological park, there are density changes in the range from 0.85 to 1.59 g m^{-3}. At the same time, in cells with a density of 1.18–1.36 g m^{-3}, above-ground grass cover is preserved, and in places with a density of 1.46–1.59 g m^{-3}, which are typical for sports grounds, paths, roads, etc. – there is no grass cover (Dragan 2012).

The mentioned and other obtained results relate to density and other physical parameters for different types of soils (Ayres et al. 2008; Bagheri et al. 2012; Henyk et al. 2014). Therefore, some obtained results related to soil compaction require detailed knowledge or their clarification. The work must be carried out taking into account the entire complex of factors involved during trampling in each individual case. We conducted this study within the path, which is located in the park zone of the city of Kyiv, in order to find out the impact of compaction on the change of physical parameters in the soil layer of gray forest soils.

The main task of the conducted research was to establish quantitative and relative indicators that reflect changes in the physical properties of gray forest soils within the path, both during anthropogenic trampling and after its termination.

2. Material and methods

Anthropogenically trampled (compacted) gray forest soils, which were formed on loess-like loams exposed in the southern part of the Holosiivo Park of Culture and Recreation named after Maksym Rylskyi, served as the object of research. According to the nature of the changes in the structure of the soil profile, they are identified as partially transformed upper horizons with the preservation of the natural profile, and according to their classification (Pozniak & Teleguz 2021), they belong to anthropogenic-natural subtypes in the types of natural soils.

According to research conducted by Nesterov (2007), the soils within the studied area of the park were formed in conditions of positive moisture balance on loess-like loams containing a significant amount of calcium carbonate. These are light gray soils characterized by a small amount of humus (up to 2%). The humus horizon reaches 20–22 cm, and a continuous whitish eluvial layer lies below it. The illuvial horizon is well defined and compacted. These soils are poor in gross nutrient reserves, especially nitrogen. Poor aeration of the upper layers and noticeable acidity reduce the intensity of microbiological processes, which causes weak mobilization of mobile forms of the nitrogen.

The trail was formed under the canopy of a mature hornbeam-oak plantation as a result of the annual trampling of the soil by vacationers and residents living in the areas adjacent to the park. Its length is from the lower dam of the third Horihuvata pond to the stop of bus 212, which is located opposite the house with the address – Horihuvata road, 19. The difference in the height of the earth's surface, from the dam to the stop bus, reaches 50 m, and part of the path, within the limits of which this study is located at an altitude of 155–160 m above sea level. The study was conducted at the three locations (Fig. 1).

The first location is represented by the stand without signs of anthropogenic trampling of the grass above-ground cover. It served as a "control" (1). The trench, to determine the physical parameters of the soil, was laid to the west of the trail. Its coordinates are 50°23'36" north latitude and 30°29'50" east longitude.

The stand belongs to derivatives for hornbeam forests and is represented by a 90-year-old stand, which consists of 1Qr2Cb4Bp2Ap1Tc. The abbreviation of tree species in the formula is as follows: Qr – *Quercus robur* L., Cb – *Carpinus betulus* L., Bp – *Betula pendula* Roth., Ap – *Acer platanoides* L. and Tc – *Tilia cordata* Mill. The height of individual trees reaches from 22 to 27 m, and this corresponds to I–II classes of productivity. The diameters of the trunks that formed the tree layer vary from 20 cm (*Carpinus betulus* L. of shoot origin) to 50 cm (*Betula pendula* Roth. of seed origin). The rest of the available trees have intermediate values of biometric indicators. The canopy closure during tree vegetation reaches more

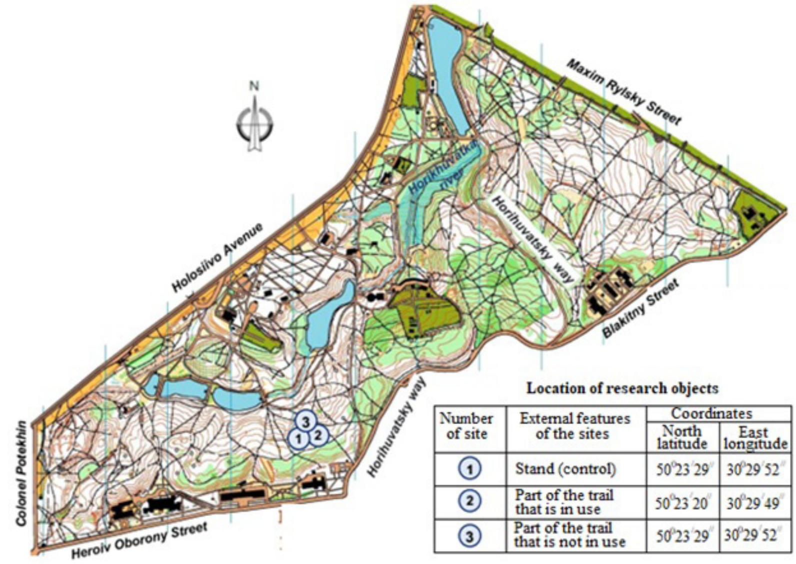

Fig. 1. The location of the research objects within the boundaries of the Holosiivo Park of Culture and Recreation named after Maksym Rylskyi.

than 0.9 units, which prevents the penetration of sunlight under the canopy of the tree stand and causes a decrease in the difference between microclimatic indicators, both on the ground's surface under the tree stand and on the part of the trail where the research was conducted. It is also worth noting that the *Betula pendula* Roth. within the limits of this phytocenosis has reached the age of natural maturity. Therefore, part of the plants of this species periodically dry up. Their trunks, having suffered a windfall or a windbreak, clutter the territory of the park and at the same time become inhabited by wood-destroying fungi as *Fomes fomentarius* [L.] Fr. and *Fomitopsis pinicola* [Sw.] P. Karst. dominate among them.

The undergrowth is of natural origin, represented by single specimens of *Acer platanoides* L. (height – 2.4 m, diameter at the root neck – 2.3 cm) and *Prunus avium* L. (height – 1.8 m, diameter near the root neck – 2.2 m). There are *Sambucus nigra* L. (height 2.9 m, diameter at the root neck – 4.2 cm) and *Euonymus europaeus* L. (height 1.4 m, diameter at the root neck – 1.7 cm) in the understore. The curtain of artificial origin is growing from *Staphylea pinnata* L. at a distance of 3 m from the trench in south direction. The distance between the plants is 1.5–2.0 m. Their height reaches 3.3 m, and the diameter near the root neck is up to 3.2 m.

The grass above-ground cover, within the limits of this location, is of medium density and has no visible signs of anthropogenic trampling (Fig. 2). It is dominated by *Carex pilosa* Scop. and *Asarum europaeum* L. The participation of *Galium aparine* L., *Lamium galeobdolon* [L.] Crantz, *Polygonatum multiflorum* [L.] All. and *Galium odoratum* [L.] Scop. in this phytocenosis is not exceeds 10%. *Impatiens parviflora* DC. and other species characteristic of hornbeam forests occur only occasionally.

The second location is a part of the trail that has been functionally used for over three decades (2). The coordinates of the place where the tranch is laid are 50°23'20" north latitude and 30°29'49" east longitude. There is no

Fig. 2. Above-ground grass cover under the tree stand without visible signs of anthropogenic trampling "control": a) general appearance of the grass cover; b) a fragment with dominance of *Asarum europeaum* L.; c) a fragment with dominance of *Galium odoratum* [L.] Scop.

Fig. 3. General view of the trail, where the impact of anthropogenic trampling on the change in physical properties in gray forest soils was investigated: a) in October 2022; b) in January 2023.

vegetation on the surface of the trail (Fig. 3). On both sides of the trail, the ground cover is dominated by curtains of *Asarum europaeum* L., the rest of the grass species characteristic of hornbeam thickets occur singly.

The third part of the trail (3) has not been functionally used for the past 15 years because of fallen trunks across its profile. Trunks of *Tilia cordata* Mill. and *Betula pendula* Roth. made it difficult for park visitors to walk along this part of the trail. The coordinates of the place where the tranch was laid are 50º23'29" north latitude and 30º29'52" east longitude. At the time of the survey, the ground surface within the trail was partially littered with the remains of a birch trunk that fell in 2014, and the natural overgrowth of soil on the trail was due to self-seeding of *Ulmus glabra* Huds. (Fig. 4a). There were up to 5 elm seedlings per 1 m^2 of land area. Their height reached up to 2.2 m, and the diameter of the trunks near the root neck – up to 2.6 cm. At the same time, the plants growing in the central part of the trail were marked with lower biometric indicators.

Herbaceous plants settled only after elm colonization of the trail. *Asarum europaeum* L. (Fig. 4b) and *Impatiens parviflora* DC. (Fig. 4c) dominated the phytocenosis that began to form. *Lamium galeobdolon* [L.] Crantz and *Pulmonaria officinalis* L. occurred singly. The height of the grass plants that populated the trail did not exceed 16 cm, and their settlement began from the edges of the trampled part.

The physical properties of gray forest soils were determined in 3-fold repetition using volumetric cylinders followed by calculation of their density and porosity indicators (ISO 11272-2001; Pozniak & Teleguz 2021).

Cylinders with a diameter of 4.8 cm, a height of 3.5 cm, and a volume of 63.30 cm^3 were used. The soil was taken in the cylinders in a natural undisturbed state. The cylinders were located along the trail at 10 cm intervals and were pressed into the soil to their full height and were closed with lids on both sides. The measurements was carried out to a depth of 50 cm, every 5 cm in 3 repetitions. At the same time, soil samples were taken from the pits to determine their moisture content. Cylinders and boxes with soil were weighed on the scales. After that, the soil in the boxes was dried at a temperature of 105 °C and weighed, and the cylinders with the soil were placed in water, where they were kept until full saturation.

Soil moisture in natural conditions was determined by the equation 1:

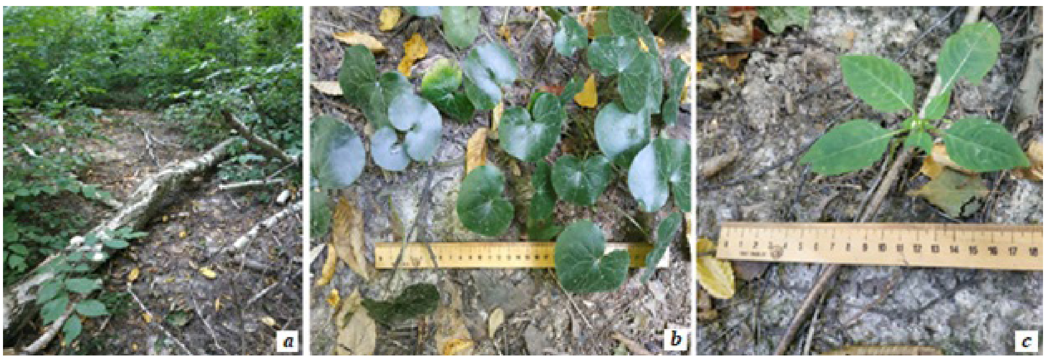

Fig. 4. Part of the trail, where changes in physical properties of gray forest soils were studied 15 years after the end of their anthropogenic trampling: a) general view of the part of the trail that has not been affected by anthropogenic trampling in the last 15 years (in the upper part – 7-year old self- seeding *Ulmus glabra* Huds.); b) a curtain of *Asarum europaeum* L., which under the canopy of *Ulmus glabra* Huds. populates the previously active compacted part of the trail; c) *Impatiens parviflora* DC., which has increased within the trail, where there was a decrease in the consistence of the soil.

$$W = \frac{A - B}{B - C} \cdot 100 \qquad [1]$$

where:
W – soil moisture under natural conditions (%),
A – mass of the box with wet soil (g),
B – mass of the box with completely dry soil (g),
C – mass of the empty bag (g),
100 – the coefficient for conversion into %.

Soil density was determined by the equation 2:

$$D = \frac{E \cdot 100}{V \cdot (100 + W)} \qquad [2]$$

where:
D – soil density (g cm^{-3}),
E – mass of the soil contained in the cylinder under natural conditions (g),
V – volume of the cylinder filled with the soil (cm^3),
W – soil moisture under natural conditions (%).

The content of pores in the natural state of the soils was determined by the equation 3:

$$PC = \frac{c - a - d}{d} \cdot 100 \qquad [3]$$

where:
PC – pore content per unit volume of soil (% of completely dry soil),
c – mass of the cylinder with soil after it is completely saturated with water (g),
a – mass of the empty cylinder (g),
d – mass of the soil in the cylinder in a completely dry state (g),
100 – the coefficient for conversion into %.

The root population of soils at the study sites was determined by the monolith method (Pozniak & Teleguz 2021). Soil samples with roots were taken with a drill, which had a cross-sectional area of 55.39 cm^2 and a working surface height of 10 cm, to a depth of 0.5 m with sampling every 10 cm. Roots isolated from monoliths, after washing on a sieve with a mesh of 0 .5 mm, were divided into small (thickness up to 2 mm, which was conditionally classified as physiologically active) and coarse (with a thickness of more than 2 mm, which is considered skeletal and performs conductive functions). The mass of the roots extracted from the monoliths, after drying in a thermostat at a temperature of 105 °C, was weighed on a laboratory scale, and the obtained results, separately for selected fractions and layers, were calculated per square meter area by equation 4.

$$M = \frac{A \cdot S}{s} \qquad [4]$$

where:
M – mass of roots contained in one square meter of soil (g),
A – mass of roots extracted by a drill from different layers of the soil, separately by fractions, (g),
S – area of a square meter (cm^2),
s – the cross-sectional area of the drill (cm^2).

The average indicators of the obtained data were calculated using the STATISTICA application program (Borovikov 2013), and the statistical significance of the difference between the investigated quantitative and relative indicators was determined (estimated) according to the Student's test (Korn, G. & Korn, T. 1984).

3. Results and discussion

The success of the growth of woody plants in urban parks usually depends on the combination and intensity of the manifestation of a complex of factors, both natural and anthropogenic. At the same time, the study of anthropogenic soil trampling deserves special attention. After all, it is precisely due to it that the surface layers of the soil are compacted, which, first of all, manifests itself in an increase in its density (volumetric mass), causes an increase in the content of solid particles per unit volume of the soil and a decrease in the volume of pores and as a result, it negatively affects the mass of physiologically active roots inhabiting the compacted soil layer.

Within the part of the trail that is in use (Fig. 3, Table 1), statistically significant compaction of gray forest soils was traced to a depth of 45 cm. At the same time, the most significant changes (t_f = 13.2) occurred in the density indicators in the upper 5-cm layer of the soil. Here, its indicators, in comparison with the control, increased by 38.0%, namely from 1.08 to 1.49 g m^{-3}. It is also worth noting that the density of the soil, in the 5–25 cm layer, with increasing depth of its determination, decreased from 1.48 to 1.44 g m^{-3}, and the maximum density value (1.52 g m^{-3}), we recorded it at a depth of 30–35 cm. This indicator was 9.4% higher than in the same layer of soil in the control area. In general, the effect of compaction on statistically reliable quantitative indicators of soil density decreases from 38.0 to 4.9% with an increase in the depth of its determination, and at a depth of 50 cm it is unreliable and limited to a difference of only 2.0%.

At the third location, 15 years after the completion of trampling, a decrease in density indicators was observed within the entire surface layer of the soil. At the same time, in the 10–50 cm layer, the density indicators were higher (by 1.6–7.1%) than in the control. However, the existing difference remained statistically unreliable (t_f = 0.2–1.2), which indicates the sufficiency of a 15-year period for the restoration of density indicators in this layer of gray

Table 1. Density of the upper 50-cm layer of gray forest soils, during and after the end of their anthropogenic trampling.

Depth [cm]	The trail research objects (locations)						
	Stand (1) "control"	Part of the trail during trampling (2)			Part of the trail 15 years after the end of trampling (3)		
	density [g cm^{-3}]	density [g cm^{-3}]	difference relative to control		density [g cm^{-3}]	difference relative to control	
			[%]	[t]		[%]	[t]
0–5	1.08 ±0.026	1.49 ±0.018	138.0	13.2	1.20 ±0.020	111.1	3.7
5–10	1.12 ±0.035	1.48 ±0.020	132.1	9.2	1.23 ±0.021	109.8	2.8
10–15	1.21 ±0.033	1.46 ±0.018	120.7	6.8	1.28 ±0.024	105.8	0.7
15–20	1.27 ±0.040	1.44 ±0.020	113.4	5.0	1.36 ±0.033	107.1	0.2
20–25	1.31 ±0.035	1.44 ±0.004	109.9	3.8	1.38 ±0.018	105.3	0.6
25–30	1.37 ±0.023	1.46 ±0.020	106.6	3.0	1.40 ±0.036	102.2	0.7
30–35	1.39 ±0.029	1.52 ±0.017	109.4	4.0	1.42 ±0.023	102.1	0.6
35–40	1.40 ±0.017	1.51 ±0.010	107.9	5.8	1.44 ±0.023	102.9	1.2
40–45	1.43 ±0.028	1.50 ±0.014	104.9	3.1	1.46 ±0.015	102.1	0.9
45–50	1.46 ±0.016	1.49 ±0.015	102.0	1.4	1.48 ±0.021	101.6	0.8

Note: Table value of quantiles of the Student's test (t) at a probability level of 0.05–2.8.

forest soils. Density indicators in the upper 10-cm layer of the studied soils remained higher (by 9.8–11.1%) than in the control, and the difference between the obtained indicators was statistically significant (t_f = 2.8–3.2), which indicates about the need to use longer periods of phytorenovation or intensification of soil rehabilitation processes, due to agro-technological measures (loosening the soil, applying fertilizers, using siderites, etc.).

The obtained density indicators are consistent and do not contradict the information related to brown mountain forest soils (Lenevych et al. 2021, Orlov et al. 2021), sod-layered soils (Ryzov & Brovko 2012), as well as soils of park and forest-park ecosystems (Henyk et al. 2014) and complement the knowledge related to the physical properties of gray forest soils (Dragan 2012).

In general, the manifestation of the degree of soil compaction, as evidenced by our research, can be identified by two relative volume indicators, namely, by the increase in the unit volume of compacted soil of solid particles and by the decrease in the volume occupied by pores, and to evaluate – by quantitative indicators that reflect the population of the soil stratum with physiologically active roots.

Long-term, fairly periodic anthropogenic trampling of the soil surface within the path was statistically reliably (t_f = 3.0–16.5) marked by the redistribution of the content of solid soil particles within its upper 45-centimeter layer (Table 2). At the same time, we recorded the maximum values of the content of solid particles (79.8%) in the upper 5-cm layer, which is 22.8% more than at the location that served as a "control". In general, under the influence of trampling, the content of solid particles in the compacted soil layer increased by 2.2–22.8% and was actually within the range of 78.1–79.8%. It is also worth noting that in anthropogenically compacted soils, the 15-year term was not enough to restore the content of solid particles naturally. The processes of recovery of the content of solid particles took place most intensively in the upper 5-cm layer. It was here that the lowest content of solid particles (71.9%) among all those recorded within this soil profile was recorded. However, the indicators of the content of solid particles in the studied soil stratum ranged from 71.9 to 78.4%, that is, they remained higher by 1.0–10.6% than at the location without visible signs of anthropogenic trampling.

This statement is consistent with data obtained Sherman et al. (2019) in Oulanka Nature Park, Finland. Evaluating the impact of anthropogenic trampling on the number of microbocenoses in the arctic soils of the Kiutakongas trail, they found out that within the limits of the trail, their total number may not change significantly. At the same time, a general trend was observed – with increasing depth from the soil surface, their number decreased (Sherman et al. 2019).

During the anthropogenic trampling of the surface of gray forest soils, as evidenced by the data in the Table. 2, the content of pores in their upper compacted 45-cm layer significantly decreases (t_f = 3.7–16.0). At the same time, the percentage of pores occupied 20.2–21.9% of the total volume, which is 7.5–44.3% less than in the control.

Determining the content of pores 15 years after the end of trampling the soil on the path (Table 2), showed that the final restoration of the content of pores did not occur during this period. At the same time, the content of pores in a unit of volume, in comparison with the indicators on the trodden part of trail, increased and amounted to 21.6–28.1%, and the difference with the indicators obtained on the control decreased by 3.5–19.7%. In general, the obtained data concerning the content of solid particles and pores in anthropogenically compacted gray forest soils are consistent with similar data obtained for sod-layered soils (Ryzhov & Brovko 2012) and complement them.

Nir et al. (2022), summarizing the research of scientists from different countries on the effect of trampling on soil compaction, showed that trampling reduces porosity in the upper 3-cm layer of the soil, and also drew attention to more angular pores in the soil under the path. The lower porosity (by 44.3%) in the 0–5 cm soil layer is indicated by the data in the Table 2, which coincide with Nair's studies. However, a significant decrease in porosity in gray forest soils can be traced to a depth of

Table 2. The content of solid particles and pores in the upper 50-cm layer of gray forest soils during and after the end of their anthropogenic trampling.

Depth [cm]	The trail research objects (locations)						
	Stand (1) "control"	Part of the trail during trampling (2)			Part of the trail 15 years after the end of trampling (3)		
	share in volume unit	share in volume unit	difference relative to control		share in volume unit	difference relative to control	
	[%]	[%]	[%]	[t]	[g cm^{-3}]	[%]	[t]
			The content of solid particles				
0–5	65.0 ±0.90	79.8 ±0.23	122.8	15.9	71.9 ±0.35	110.6	7.1
5–10	69.4 ±0.56	79.2 ±0.20	114.1	16.5	74.3 ±0.29	107.1	7.8
10–15	73.3 ±0.45	78.6 ±0.26	107.2	10.2	75.8 ±0.23	103.4	5.0
15–20	73.9 ±0.49	78.3 ±0.44	106.0	8.2	75.9 ±0.15	102.7	3.9
20–25	74.8 ±0.12	78.9 ±0.67	105.5	6.0	76.7 ±0.23	102.5	7.3
25–30	75.1 ±0.38	78.1 ±0.50	104.0	4.8	76.8 ±0.17	102.3	4.1
30–35	75.3 ±0.48	79.5 ±0.55	105.6	5.7	77.2 ±0.16	102.5	3.8
35–40	76.1 ±0.42	79.3 ±0.36	104.2	5.8	77.6 ±0.23	102.0	3.0
40–45	77.2 ±0.32	78.9 ±0.18	102.2	3.0	78.0 ±0.18	101.0	3.1
45–50	78.2 ±0.21	78.7 ±0.15	100.6	1.9	78.4 ±0.22	100.3	0.7
			Content of pores				
0–5	35.0 ±0.90	20.2 ±0.21	55.7	16.0	28.1 ±0.35	80.3	7.2
5–10	30.6 ±0.56	20.8 ±0.20	68.0	9.8	25.7 ±0.29	84.0	7.6
10–15	26.7 ±0.45	21.4 ±0.26	80.2	10.1	24.2 ±0.23	90.6	4.9
15–20	26.1 ±0.49	21.7 ±0.43	83.1	7.4	24.1 ±0.15	92.3	4.6
20–25	25.1 ±0.15	21.1 ±0.67	84.1	5.8	23.3 ±0.24	92.8	6.4
25–30	24.9 ±0.28	21.9 ±0.50	88.0	5.2	23.2 ±0.17	93.2	5.2
30–35	24.7 ±0.48	20.5 ±0.55	83.0	5.6	22.8 ±0.18	92.3	3.7
35–40	23.9 ±0.42	20.7 ±0.36	86.6	5.9	22.4 ±0.22	93.7	3.1
40–45	22.8 ±0.32	21.1 ±0.18	92.5	3.7	22.0 ±0.16	96.5	2.2
45–50	21.8 ±0.21	21.3 ±0.15	97.7	1.8	21.6 ±0.24	99.1	0.6

Note: Table value of quantiles of the Student's test (t) at a probability level of 0.05–2.8.

45 cm (t = 3.7), and after the end of the anthropogenic load to a depth of 40 cm (t = 3.1), which indicates a slow process of soil porosity recovery.

Research by Silva et al. (2011) found that microbial activity, transformation of carbon and nitrogen compounds, usually occurs inside small pores. In our case (Table 2), a decrease in porosity was observed by 7.5–44.3%, which undoubtedly affects not only microbial activity (Ryzhov et al. 2013), but also carbon and nitrogen content in anthropogenically compacted soils (Ryzhov et al. 2014). It was noted that the stability of the soil absorbing complex is strongly affected by excessive compaction of the soil stratum (Silva et al. 2011). After all, the rate of carbon mineralization decreases with an increase in soil density, and this leads to an increase in the accumulation of organic matter in moderately compacted soil layers.

It is also worth noting that the indicators of density, the content of solid particles and pores, recorded by us during this study and given in the Table 1 and 2 caused rather problematic prerequisites for the development, preservation and reproduction of physiologically active roots, both in the upper 10 cm and in the 50 cm layer of gray forest soils. This assumption is quite convincingly confirmed by the data given in the Table 3.

Table 3. Population of physiologically active roots of woody plants in the upper 50-cm layer of gray forest soils during and after the end of their anthropogenic trampling.

Depth [cm]	The trail research objects (locations)						
	Stand (1) "control"	Part of the trail during trampling (2)			Part of the trail 15 years after the end of trampling (3)		
	root content	root content	difference relative to control		root content	difference relative to control	
	[g m^{-2}]	[g m^{-2}]	[%]	[t]	[g m^{-2}]	[%]	[t]
0–5	410 ±6.7	36 ±0.5	8.8	55.7	119 ±4.4	29.0	36.3
5–10	279 ±8.8	43 ±0.9	15.4	26.7	138 ±2.1	49.5	15.6
10–15	100 ±2.8	36 ±1.3	36.0	20.7	67 ±3.2	67.0	7.8
15–20	98 ±3.7	33 ±1.1	33.7	16.8	42 ±1.0	42.8	14.6
20–25	72 ±1.9	32 ±1.2	44.4	17.8	38 ±0.9	52.8	16.2
25–30	61 ±2.0	26 ±0.6	42.6	16.8	34 ±0.7	55.7	12.7
30–35	26 ±0.2	16 ±0.5	61.5	18.6	20 ±0.8	76.9	7.3
35–40	16 ±0.1	13 ±0.3	86.7	9.5	14 ±0.6	93.3	3.2
40–45	13 ±0.2	11 ±0.3	84.6	5.5	12 ±0.3	92.3	2.8
45–50	12 ±0.2	9 ±0.3	75.0	8.3	11 ±0.2	83.3	3.5
Σ 0–50	1,087 ±5.5	255 ±0.4	23.6	150.9	495 ±5.1	45.6	78.9

Note: The tabular value of the quantiles of the Student's test at the 0.05 probability level is 2.3.

The mass of physiologically active roots decreased catastrophically (by 4.3 times, compared to the control) and amounted to only 255 g m^{-2} in soils that were constantly trampled and localized within the active trail. It was 76.4% less than in the plot that served as a control. At the same time, in all 10 selected layers of the soil, the difference between the mass of physiologically active roots recorded on the experimental site and the control was statistically significant (t_f = 5.5–55.7) and the greatest loss of root mass (91.2%) was observed in the upper 5-cm layer of the active trail.

The accounting of roots in the 0.5-cm soil layer of the trail, 15 years after its extraction from anthropogenic trampling, indicates a positive dynamic, which refers to the restoration of the mass of physiologically active roots during the mentioned period. Thus, the total mass of roots, in a 0.5-cm thickness, at the time of the examination, was 495 g m^{-2}, which is 2.2 times less than in the control. At the same time, the indicators of root mass obtained within 10 layers are differed significantly (t_f = 2.8–36.3) from the indicators recorded in the control. The mass of roots in the soil layer of this trail was smaller and was 29.0–93.3% of their mass in the control, but greater in 1.1–3.3 times than in the soil layer of the active trail. It is also worth noting that the largest mass of roots in 3.2–3.3 times more than on the existing trail was recorded in the upper 10-cm layer of soil inhabited by physiologically active roots of the 7-year-old self-sowing *Ulmus glabra* Huds., which actually contributed to the course of renovation processes within this location.

4. Conclusions

It is shown that in the gray forest soils exposed under the trail of the Holosiivo Park, statistically significant changes in their density, the content of solid particles and pores, as well as the mass of physiologically active roots of woody plants can be traced to a depth of 45 centimeters. The upper 10-cm layer of gray forest soils, undergoes the greatest degradation changes due to existing constantly acting trampling. There was an increase in density in this layer by 32.1–38.0% and the content of solid particles of the soil by 14.1–22.8%, as well as a decrease in the volume of pores by 32.0–44.3% and the mass of physiologically active roots of woody plants growing on the side of the trail by 84.6–91.2%.

A 15-year period is not enough for the natural recovery of the investigated physical indicators in a 50-cm layer of compacted soils, and the most positive changes were clearly visible in the upper 5-cm layer. In particular, compared to location 2 in this layer, a decrease in density by 19.5% and the content of solid particles by 9.9%, as well as an increase in the content of pores by 39.1% and physiologically active roots was observed by 330.0%.

The restoration of physical indicators in anthropogenically compacted soils occurs with the participation of self-seeding *Ulmus glabra* Huds. within the southern part of the Holosiivo Park. The species quite intensively inhabits the trail space that is not trampled, and its roots contribute to the loosening of the soil layer.

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