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Water-physical properties of gray forest soils and their root settlement in areas of anthropogenic trampling

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Abstract. The aim of the study was to monitor the impact of anthropogenic trampling of gray forest soil on their content of water, air, solid particles and the mass of fine and coarse roots. The contents of mass of solid particles, volume of air, water and its permeability were determined according to generally accepted methods using of measuring cylinders. Soil roots colonization was measured by the method of "monoliths". It was found out that under the impact of anthropogenic trampling, water reserves in the upper 50-centimeter layer of soils were 1.6-5.3% higher than under matured oak-hornbeam stand without visible signs of degradation, and the soil water saturation coefficient during the research was lower (0.21-0.43%) than the optimal values (0.80%). At the same time, the greatest destruction changes were experienced by the researched physical indicators in a humus horizon of gray forest soils. An increase of solid particles (by 14.1-22.8%), decrease of air pores (by 32.0-44.3%) and the mass of fine roots of trees (by 84.6-91.2%) in the 10-cm soil layer were recorded. It is found that in the event of cessation of trampling of the path surface, the natural recovery of degraded physical indicators in compacted soils happens most intensively in the 5-centimeter horizon. At the same time the changes in the decrease of solid particles (by 9.9%), an increase of pores (by 39.1%) and fine roots of trees (by 330.0%) were observed over a 15-year period. The obtained quantitative and relative indicators of the content in anthropogenically compacted soils of solid particles, water and air explain the features of its settlement by roots of vegetation, and also indicate the applied significance of the results presented in the study

Keywords: soil compaction; permeability; park plantings; aboveground cover; soil colonisation by roots

Introduction

Anthropogenic trampling of the soil surface is most significantly manifested within urban landscapes especially in green plantations, where the negative consequences of trampling are manifested due to the deterioration of their ecological functions, as well as in soil dehumification and increased manifestation of external signs of erosion processes and a decrease in the number, or even the complete disappearance of certain species from plant communities. Usually, soil compaction causes functional changes in edaphotopes, and also affects the quantitative and relative indicators related to the species composition of plant cover and affect the microclimatic indicators of the surrounding areas.

Studies on this topic have been conducted in various regions, highlighting the consequences of human activities. N. Nir *et al.* (2022) analysed the long-term paedogenic and geomorphological effects of human trampling. Their findings indicate that persistent recreational impacts lead to soil compaction, changes in water infiltration, and erosion, with far-reaching consequences for ecosystems. Researches D. Selesa & A. Cerda (2020) presented a comprehensive review of soil erosion on mountain trails caused by recreational activities. The researchers emphasised the role of soil hydro-physical properties in degradation processes, particularly the reduction in moisture retention and infiltration capacity under human pressure. Numerous studies on trampling of recreational areas have confirmed the reduction in the number of woody and herbaceous species, their cover density, reduction in increment of wood and suppression of growth (Atic *et al*. 2009; Li *et al*., 2020).

Scientists M. Kissling *et al.* (2009) investigated short- and long-term effects of trampling in suburban beech forests. They observed that trampling causes soil compaction, reduces organic matter content, and disrupts microbial processes. These changes impair soil fertility and natural nutrient cycling. Ya. Henyk *et* *al.* (2014) examined changes in the physicochemical properties of soils in urban parklands and woodlands in Ukraine under recreational load. Their findings revealed decreased porosity, reduced water permeability, and increased soil compaction due to trampling, which limits root growth.

The beginning of digressive changes in phytocenoses that occur during trampling is visually determined by the degree of degradation of vegetation cover. With permissible soil compaction, the result of trampling is clearly visible within the paths, playgrounds, recreational objects, which can be evaluated by the degree of recreational digression and degradation of grass cover (Lenevych *et al*. 2021; Kalahroudi *et al.,* 2023).

The problems associated with anthropogenic soil trampling began to take on clear outlines from the second half of the 20th century and have now become the subject of research by both researches and scientists in various fields of knowledge, which relate to the ecology of plantations of natural and artificial origin. During this long period, it was found that soil compaction causes changes in the structure of the soil, as well as their physical properties. This is manifested in changes in soil porosity, deterioration of their temperature regime and water-physical properties. These changes negatively affect the nutrition regime of woody and herbaceous plants. In particular, O. Ryzhov *et al.* (2014) studied that for sandy soils, the optimal density (volumetric mass) is within 1.20-1.45 g/m^3. If the soil compaction is 1.20 g/m^3 and less – the soil is not retained moisture. The plants suffer greatly from its lack. It negatively affects the growth and functioning of the root systems of woody plants.

The mentioned information on water-physical properties refers to different types of soils, and therefore the clarification of the impact of anthropogenic on their forest vegetation properties should be carried out with the involvement of the same type of research methods with subsequent detailing and clarification of the obtained results.

The main aim of the study was to find quantitative and relative indices that reflect the impact of anthropogenic trampling on the water content, solid particles and cracks in gray forest soils and their population by roots.

Materials and Methods

The research was conducted in compliance with the ethical standards set forth in the Convention on Biological Diversity (1992). The research object was a path located in the southern part of Holosiivo Park of Culture and Recreation named after Maksym Rylskyi, in the Kyiv city. The height of exceedance, in the range from the lower dam of the third Horikhuvatskyi pond (coordinates: 50°23´26´´ N and 30°30´88´´ E) to the stop of bus 212 (coordinates 50°23´46´´ N and 30°30´24´´ E), reaches 50 m and the objects of this study are at an altitude of 155-160 m above sea level. The current contours of the path were formed more than 30 years ago, as a result of annual trampling of the soil surface by residents of the areas adjacent to the park, vacationers and students studying at the National University of Life and Environmental Sciences of Ukraine (Brovko *et al.*, 2023).

The formation of the research object occurred in the summer of 2004, when a *Tilia cordata* Mill. tree blocked a hiking trail due to a windstorm (Nesterov, 2007). The field research was carried out in August 2019 and the desk work – in 2020-2021. The study was conducted within the path, which was located in 90-year-old oak-hornbeam stand in the park space of the Kyiv city, in order to estimate the impact of anthropogenic pressure on the changes of water-physical indicators in the gray forest soils. The path was trampled under the plantation formed of deciduous woody plants, among which, at the time of the research, five species dominated, and their share in the composition of the tree layer was *Quercus robur* L., *Betula pendula* Roth., *Carpinus betulus* L., *Tilia cordata* Mill., *Acer platanoides* L., which indicates its derivative origin, because it grows in the area belonging to hornbeam groves (Holosiivskyi National Nature Park, n.d.).

The diameters of the trees were quite variable and ranged from 20 cm (hornbeam, sapling origin) to 50 cm (birch, seed origin), and the height of the trees that formed the main layer of the plantation reached from 22 up to 27 m, which in terms of productivity corresponds to higher classes of productivity. Intermediate values of biometric indicators were observed in the rest of the trees present on the site. The canopy closure, during the vegetation period of the trees, reaches more than 0.9 units. That prevents the penetration of sun's rays under the canopy on hot summer days, providing the much-desired coolness for park visitors.

Studies conducted by Y. Nesterov (2007) in this area of Holosiivskyi Park showed the drying out of birch and its loss from the stand. It is also worth noting that over the past 15 years in this phytocenosis there has been a drying up of the birch (Fig. 1a).

a *b* *c*

Figure 1. Dead trunks of birch within the path area
Note: a) trunks that have fallen from the composition of the stand; b) fallen trunk near the path; c) trunk that fell into an area without visible signs of trampling the soil
Source: authors' photo

Usually, the root systems of birches die, and therefore their trunks fall out of the ground, both near anthropogenically trampled areas (Fig. 1b), and in areas where the soil surface does not have visible signs of trampling of grass cover (Fig. 1c), which testifies to the complexity of this phenomenon, which is apparently connected not only with the compaction of the soil layer, but also with the birch reaching the age of natural ripeness.

Tree trunks with dead roots, after being blown down by the wind, not only clutter up the territory of the park and worsen the aesthetic appeal of the area, but also become inhabited by different pathogens and wood-destroying fungi, in particular *Fomitopsis pinicola* and *Fomes fomentarius*, which significantly accelerate the natural decomposition of dead wood.

Soils within the studied part of the park, by the nature of changes in the structure of the soil profile, belonged to partially transformed upper horizons with a preserved natural profile and according to classification (Pozniak & Teleguz, 2021) were identified as anthropogenic-natural subtypes that belong to types of natural soils. According to Y. Nesterov (2007) these were gray forest soils. That type of soil formed on loess loams. They were characterised by a humus horizon 20-22 cm thick, an insignificant humus content (up to 2%) and unsatisfactory aeration of the upper layers of the soil, which against the background of the available acidity (saline pH = 4.3-4.5) negatively affected the course of microbiological processes and as a result, it was manifested by a weak mobilisation of mobile forms of nitrogen.

The study of the impact of soil compaction on the content of water resources in them and on their settlement by roots was carried out within three locations of this plantation. The first (1), without visible signs of anthropogenic trampling of the grass topsoil, was located at coordinates 50°23´36´´ N and 30°29´50´´ E and served as a "control". The second, a path that had been used as intended for over three decades (2). The site where samples were taken for research was located at the coordinates 50°23´20´´ N and 30°29´49´´ E. There was no vegetation cover on the surface of the path (Fig. 1). The third part of the path, which had not been used for its functional purpose for the past 15 years (3), due to the fact that dead trunks of *Tilia cordata* Mill fell across the path in 2007 year (Nesterov 2007) and *Betula pendula* Roth., which made it impossible for park visitors to pass comfortably along this part of the path. The coordinates of the sampling site for the study were 50°23´29´´ N and 30°29´52´´ E. At the time of the survey, this part of the path was littered with the remains of a dead birch trunk that fell in 2014, and its natural overgrowth, occurred due to self-sowing of *Ulmus scabra* L., (there were up to 5 pc./m^2). The height of the seedlings reached up to 2.2 m, and the diameters of their trunks at the root neck – up to 2.6 cm. It was also worth noting that lower biometric indicators of the trunks were observed in the seedlings that grew in the central part of the path.

Water and physical properties of studied soils were determined in 3-5 repetitions. Test samples were selected in every 5 cm in the depth to 50 cm. In particular, soil moisture in its natural state was determined according to formula (1):

$$W_M = \frac{W_V}{M_{CS}} \cdot 100, \quad (1)$$

where: W_M – soil moisture in its natural state, in weight %; W_V – the mass of water that evaporated from the weight of the soil during its drying, g; M_{CS} – weight of the soil in a completely dry state, g.

The compaction of the soil structure in a completely dry state was determined by formula (2):

$$D_S = \frac{E \cdot 100}{V \cdot (100 + W_M)}, \quad (2)$$

where: D_S – compaction of the soil in a completely dry state, g/cm^3; E – mass of wet soil in the cylinder, without the mass of the cylinder, g; V – the volume of the cylinder used for soil sample selection, cm^3; W_M – water content in the soil, in its natural state, in weight %.

The calculation of the water content in the upper 50-centimeter soil layer was carried out according to formula (3):

$$B = a \cdot d_v \cdot h, \quad (3)$$

where: B – water content, m^3/ha; a – moisture content of the soil layer, in weight %; d_v – compaction of the soil layer, g/cm^3; h – soil layer in which the water content was determined, cm.

The water permeability of the upper 10-centimeter layer of soil was determined by alternating water pressure to wet the soil outside the recording site, the cylinder that limited the contours of the site was placed in the middle of a larger cylinder (52.78 cm^2) filled with water. During the experiment, the same water level was maintained in both cylinders. Calculation of water permeability of the soil was carried out according to formula (4):

$$K = \frac{G}{S \cdot T} \cdot K_{10}, \quad (4)$$

where: K – water permeability of the soil, ml/h; G – the amount of water supplied to the accounting site, 1000 ml; S – the area of the accounting site, 26.86 cm^2; T – duration of water absorption, h; K_{10} – coefficient of reduction to a temperature of 10°C (1.0075).

The assessment of water permeability of the soil, within the studied locations, was carried out according to the Kaczyński scale. The scale consists of 6 positions, namely (in mm/hour): failed – >1000; excessively high – 1000-500; the best – 500-100; good – 100-70; satisfactory – 70-30; unsatisfactory - <30.

To determine the content of solid particles, water, air, cracks and the coefficient of their saturation with water, cylinders with a volume of 61.64-67.40 cm^3 were used. Soil in an undisturbed state was collected in cylinders in 5-fold repetition, weighed on the laboratory scales, the obtained results were recorded in the field journal. After that, the soil cylinders were saturated with water until the change in their mass stopped. Then, repeated weighing of cylinders with soil saturated with water was carried out. The obtained data and the mass of the soil at natural humidity were converted to completely dry soil according to formula (5):

$$N_{CS} = \frac{M_V \cdot 100}{V_C \cdot (100 + W_P)}, \quad (5)$$

where: M_{CS} – mass of soil in a completely dry state, in 100 cm^3, g; M_V – soil mass, in a cylinder at natural water content, g; V_S – cylinder volume, cm^3; W_P – water content in the soil under natural conditions of determination, %.

The content of the soil, in cylinders saturated with water, under natural humidity and in a completely dry state, was converted to its content in 100 cm^3, by dividing the mentioned indicators by the volume of the cylinders that contained the soil, and the obtained result was multiplied by 100 (cm^3).

The content in 100 cm^3 of solid particles (absolutely dry soil), water (the difference between the soil saturated with water and the absolute dry mass of the soil, identified as the content of cracks), air (water that displaced the air) was determined, in %, by formula (6):

$$X_P = \frac{M_P \cdot 100}{N_{NW}}, \quad (6)$$

where: X_P – content in 100 cm^3 of the soil of the studied components, in % by volume; M_R – content in 100 cm^3 of the studied component, g; M_{NW} – content in 100 cm^3 of soil completely saturated with water, g.

The coefficient of water saturation of cracks in the soil was determined by formula (7):

$$K_{NW} = \frac{N_W}{M_{PC}}, \quad (7)$$

where: K_{NW} – soil water saturation coefficient, under natural conditions, a dimensionless value; M_W – water content in 100 cm^3 of soil under natural conditions of determination, g; M_{PC} – water content that filled all the cracks in 100 cm^3 of soil, g.

The content of roots in the upper 50-centimeter soil layer at the studied locations was determined by the monolith method (Pozniak & Teleguz, 2021) in 5-fold repetition. Soil samples with roots were taken with a drill with a cross-sectional area of 55.39 cm^2 and a height of the working surface of 10 cm. The root mass content in the studied soil layer was determined according to the method described in the article F. Brovko *et al.* (2023).

The average values were calculated using Microsoft Excel and STATISTICA 8.0 programme packages (Paianok & Zadorozhnia, 2020). The significance of the difference between the means of obtained data was evaluated using Student's t-test.

Results

The results of determining the water content under the canopy of a 90-year-old stand are shown in the Table 1. The data shows that in the upper 50-cm soil layer at the three studied locations, the quantitative indicators of water reserves had insignificant differences (Student's criterion 0.2-2.7). In particular, at the location without signs of trampling, a 50-cm layer of gray forest soils contained 476.2 ± 5.79 m^3/ha of water. At the same time, on the section of the path, which has been used as intended for more than 30 years, the water reserves in the 50-cm soil layer were 5.3% higher than on the "control" and amounted to 501.6 ± 7.46 m^3/ha, which, in our opinion, is due to the lack of water transpiration by plants within the path, and at the location where the path was decommissioned 15 years ago, the difference with the "control" was only 1.6%, which in quantitative terms is identified by the indicator 483.9 ± 7.66 m^3/ha and is associated with physiological by the consumption of water by the plants inhabiting the path space.

Table 1. Water content in the upper 50-cm layer of gray forest soils formed on loess-like loams

Depth of determination, cm	Under the canopy of a 90-year-old plantation, composition* 1Qr2Cb4Bp2Ap1Tc						
	(1) without signs of trampling, "control", m^3/ha	part of the path that:					
		(2) used for more than 30 years, m^3/ha	relatively "control"		(3) unused for 15 years, m^3/ha	relatively "control"	
			%	t		%	t
0-5	67.0 ± 5.09	73.6 ± 2.82	109.8	1.1	64.7 ± 1.78	96.6	0.4
5-10	74.6 ± 1.49	83.9 ± 4.32	112.4	2.0	73.3 ± 1.03	98.2	0.7
10-15	50.0 ± 3.04	47.7 ± 1.94	95.4	0.6	51.2 ± 0.79	104.2	0.4
15-20	46.2 ± 1.86	46.6 ± 3.14	100,9	0.1	46.7 ± 0.30	101.1	0.3
20-25	37.3 ± 1.66	38.8 ± 1.57	104.0	0.7	39.3 ± 1.02	105.4	1.0
25-30	39.8 ± 1.36	41.6 ± 2.98	104.5	0.6	40.4 ± 0.92	101.5	0.4
30-35	38.9 ± 3.57	41.5 ± 1.72	106.9	0.7	41.1 ± 0.88	105.6	0.4
35-40	39.7 ± 1.24	43.4 ± 2.54	109.3	1.3	41.6 ± 0.59	104.8	0.6
40-45	38.9 ± 1.11	39.5 ± 1.92	101.5	0.3	40.9 ± 1.01	195.1	1.3
45-50	43.8 ± 3.38	45.0 ± 1.28	102.7	0.3	44.7 ± 1.20	102.0	0.2
∑ 0-50	476.2 ± 5.97	501.6 ± 7.46	105.3	2.7	483.9 ± 7.66	101.6	0.8

Note: *) Qr – *Quercus robur* L.; Cb – *Carpinus betulus* L.; Bp – *Betula pendula* Roth.; Ap – *Acer platanoides* L.; Tc – *Tilia cordata* Mill. Table value of quantiles of Student's test (t) at probability level 0.05-2.8
Source: developed by the authors

Determination of water saturation coefficients of cracks in the upper 50-centimeter soil layer (Table 2) showed that at the time of the survey, their field indicators were outside the optimal values typical for woody plants (0.80), and significant differences between the obtained values were traced up to 45-centimeters deep. At the location 1 ("control"), the coefficients of water saturation of cracks were in the range of 0.13-0.23 units, and on the exploited path they were 22.2-87.0% higher than on the "control". At the location where the path has not been operated for the last 15 years, the difference between the saturation coefficients compared to the "control" was smaller and amounted to 16.7-66.7%. It is also worth noting that the studied sites are located at highland (155-160 m above sea level), and therefore, the mode of providing them with water resources occurs exclusively due to atmospheric precipitation and significantly depends on their presence or absence, as well as on their frequency of precipitation, intensity and duration in time. The rate of water seepage in different locations of anthropogenic trampling of the path is shown in the Table 3.

Table 2. Coefficient of saturation of cracks with water in the 50-cm soil layer, volume %

Depth, cm	Under the canopy of a 90-year-old plantation, composition 1Qr2Cb4Bp2Ap1Tc						
	(1) without signs of trampling, "control", %	part of the path that:					
		(2) used for more than 30 years, %	relatively "control"		(3) unused for 15 years, %	relatively "control"	
			%	t		%	t
0-5	0.21 ± 0.008	0.39 ± 0.006	185.7	18.0	0.26 ± 0.004	123.8	4.5
5-10	0.23 ± 0.006	0.43 ± 0.006	187.0	25.5	0.34 ± 0.005	147.8	14.1
10-15	0.18 ± 0.004	0.24 ± 0.006	133.3	8.3	0.30 ± 0.004	166.7	5.0
15-20	0.16 ± 0.004	0.23 ± 0.006	143.8	9.7	0.26±0.003	162.5	20.0
20-25	0.16 ± 0.004	0.20 ± 0.008	125.0	4.5	0.22 ± 0.002	137.5	13.3
25-30	0.17 ± 0.003	0.20 ± 0.006	117.6	4.5	0.21 ± 0.002	123.5	11.1
30-35	0.17 ± 0.003	0.21 ± 0.009	123.5	4.2	0.21 ± 0.003	123.5	9.5
35-40	0.13 ± 0.002	0.23 ± 0.007	176.9	13.7	0.20 ± 0.002	153.8	25.0
40-45	0.18 ± 0.004	0.22 ± 0.002	122.2	8.9	0.21 ± 0.002	116.7	6.7
45-50	0.21±0.005	0.22±0.003	104.8	1.7	0.22±0.004	104.8	1.6

Note: table value of quantiles of the Student's test (t) at a probability level of 0.05-2.8
Source: developed by the authors

Table 3. The rate of water filtration in the upper 10-cm layer of gray forest soils

Object number	The place of determination, under the canopy of a 90-year-old tree stand, composition 1Qr2Cb4Bp2Ap1Tc	Depth of determination, cm	Water filtration rate, mm/h	Relatively "control"	
				%	t
1	Location – without signs of trampling "control"	0-5	226 ± 6.9	100.0	-
		5-10	191 ± 5.0	100.0	-
Locations – part of the path:					
2	which has been used as intended for more than 30 years	0-5	22 ± 0.7	9.7	29.4
		5-10	18 ± 0.7	9.4	34.3
3	15 years after the end of its intended use	0-5	76 ± 1.2	33.6	21.4
		5-10	78 ± 1.9	40.8	21.1

Note: table value of quantiles of the Student's test (t) at a probability level of 0.05-2.3
Source: developed by the authors

The data of Table 3 indicate that the compaction of the upper 10-cm layer significantly affects their ability to absorb and filter water. Thus, at the location 1, in our case the "control", it was the "best" rate of water filtration, and its quantitative indicators were in the range of 191 ± 5.0 - 226 ± 6.9 mm/h and significantly prevailed (t = 21.1 - 34.3). The rate of water filtration on the path, where the compacted soils were characterised by "unsatisfactory" filtration, which was in the range of 18 ± 0.7 - 22 ± 0.7 mm/h, and this was only 9.4-9.7% of the values obtained on "control". Removal of a part of the path from operation (location 3) shows that over a 15-year period compacted gray forest soils are only able to partially restore the rate of water filtration (up to 76 ± 1.2 - 78 ± 1.9 mm/h) in a natural way, and this is 33.6-40.8% of the indicators characterizing the control location and convincingly indicates the need to develop more effective measures related to the prevention of anthropogenic trampling on soil compaction.

The upper 10-centimeter layer of gray forest soils within the existing path was characterised by a lower rate of water filtration (by 10 times) than locations without signs of trampling, and this significantly increased the probability of the occurrence and development of erosion processes. At the same time, during heavy rains or downpours, water erosion centres began to form on the edges of the path, where the soil was less compacted than in the central parts of the path. With increasing angles of inclination of the soil surface on the path and with the concentration of water flows, the entire trampled part of the path can be eroded.

As evidenced by the data shown in Figure 2, anthropogenic trampling causes significant changes in the ratio of solid particles, air and water in their upper 45-cm layer (t = 3.0-42.7) and negatively affects its population with physiologically active (fine) roots. In particular, at the first location without signs of the aboveground cover (Fig. 2a), the content of hard particles per unit of soil volume have been varied from 65.0 ± 0.90 till 77.2% ± 0.32. At the same time, cracks were characterised by fairly good aeration (18.6 ± 0.35 - 27.7 ± 0.98%) and insufficient water saturation (3.2 ± 0.07 - 7.3 ± 0.09%). It was at this location, in the 50-cm soil layer of the 90-year-old stand under study, the highest content of physiologically active roots (1087 ± 5.5 g/m^2), of which 72% of roots mastered the upper 15-cm layer.

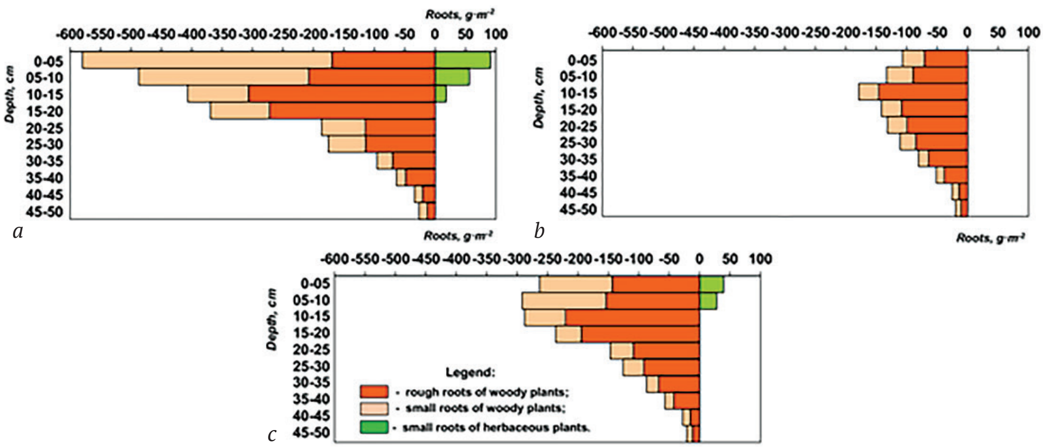

Figure 2. The content of hard particles, air, and water in the 50-cm layer of soils and its population with fine roots at the locations

Note: a) without visible signs of trampling of the topsoil; b) part of the path used by pedestrians for more than 30 years; c) part of the path that has not been used for the last 15 years

Source: developed by the authors

During the study at the first location, it was found out that of the available 1943.4 g/m^2 coarse roots of the birch in the upper 20-cm layer of light gray forest soil, 50.8% belonged to the dead, which is actually the main reason for the presence of dead trunks of the birch on the site, with root systems that have completely fallen out of the soil. The accounting of existing roots with the involvement of the monolith method showed (Fig. 3) that their largest mass (2423.9 ± 3.79 g/m^2) was observed in the upper 50-centimeter layer at the control location (Fig. 3a). Of the total mass of roots belonging to woody plants, the fraction of fine roots was 44.9% (1088.3 ± 5.43), and coarse – 55.1% (1335.6 ± 4.58 g/m²). At the same time, the largest mass of fine roots (410.2 ± 6.73 g/m²), which was 37.7% of their total mass, in the upper 5-centimeter layer have been recorded.

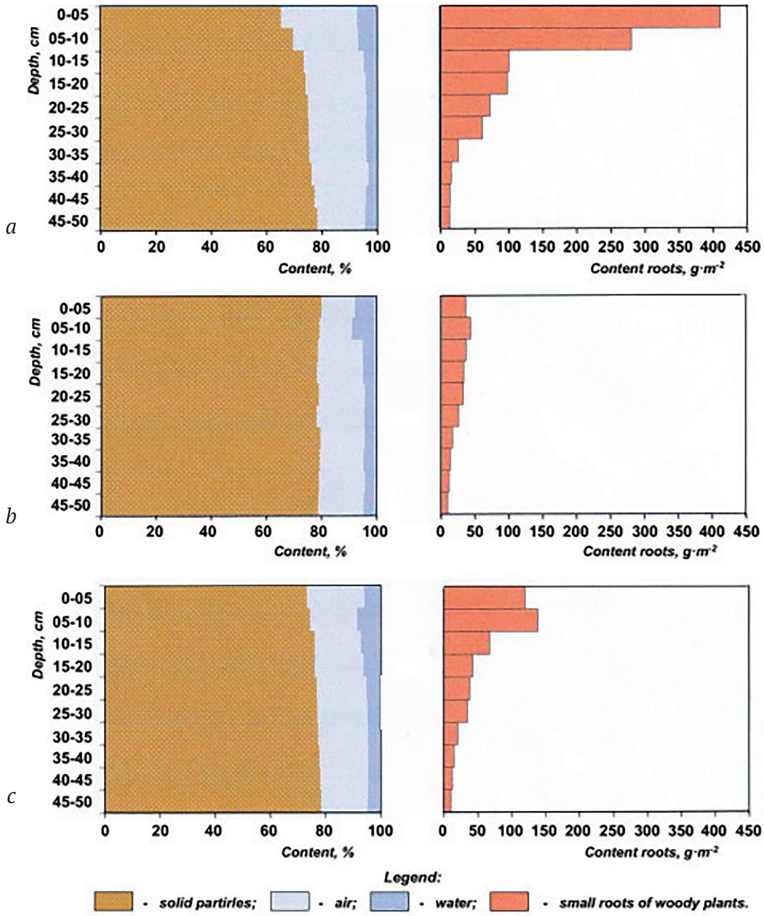

Figure 3. Inhabitation by roots of the upper 50-centimeter soil layer at locations
Note: a) without visible signs of trampling of the topsoil; b) part of the path used by pedestrians for more than 30 years; c) part of the path that has not been used for the last 15 years
Source: developed by the authors

Coarse roots dominated the 10-15 cm soil layer (Fig. 3a, 3c). Their share, from the total mass of available roots, was 22.9% (306.5 ± 8.50 g/m²). The bulk of the available roots (74.0%) grew in the 20-cm layer of the soils. Roots of herbaceous plants, dominated by *Carex pilosa* Scop. and *Asarum europaeum* L., mastered the upper 15-centimeter layer. The mass of their roots was 165.3 ± 1.35 g/m², which was 4.8 times less than the fine roots of trees that inhabited the same soil layer. The maximum share of the mass of the roots of grass plants (55.1%) was recorded at this location was in the 0-5 cm layer. With depth, the content of roots decreased to 34.0% in the 5-10-cm layer and to 10.9% in the 10-15-cm layer.

At the second location, where a part of the path has been used for more than 30 years (Fig. 3b), the action of anthropogenic trampling significantly affects the population of the 50-centimeter layer of soil (t_f = 276.9). After all, their mass decreased by 40.6% compared to the "control" and during the experimental work, it was identified at the level of 983.4 ± 3.56 g/m^2. Trampling had a particularly unfavourable effect on the development of fine roots in woody plants. Their mass, in comparison with the "control", decreased by 4.3 times and amounted to only 275.9 ± 0.45 g/m^2. Coarse roots, more resistant to soil compaction, this is indicated by their mass (725.5 ± 3.25 g/m^2), which decreased in comparison with the "control" by 1.8 times. It is also worth noting that there were no herbaceous plants at this location, and the fine roots of woody plants, in order to master the compacted layers of the soil, penetrated them through the dead fragments of coarse roots (Fig. 4).

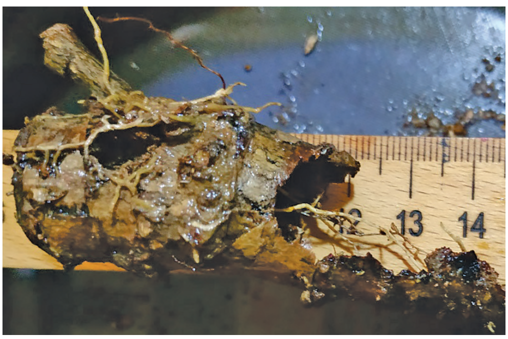

Figure 4. Fine roots of woody plants growing in a fragment of a dead coarse root (second location)
Source: authors' photo

At the third location, where a part of the path has not been used for the last 15 years (Fig. 1c), certain changes related to the improvement of the ecology of the environment took place during this period. In particular, herbaceous plants settled on the site, among which *Asarum evropaeum* L. and *Impatiens parviflora* DC. occupied a dominant position. *Pulmonaria oficinalis* L. and *Lamium galeobdolon* L. occurred singly. Their height did not exceed 16 cm, and their roots, at the time of the study, mastered only the upper 10-centimeter soil layer. At the same time, the mass of the roots was insignificant and amounted to 67.6 ± 0.87 g/m^2. From this mass, 58.4% of the roots were developed in the 0-5 cm soil layer, and 41.6% – in the 5-10 cm layer.

The total mass of the roots of woody plants inhabiting a 50-cm thick layer of gray forest soils at the third locations was 1545.7 ± 11.20 g/m^2, which was 63.8% of the total mass of roots recorded in the "control" and 23.2% more, than in the second location. Actually, it is by this percentage that the total mass of roots at this location has increased over the past 15 years. At the same time, the mass of fine roots was 45.7% of their mass in the "control" (496.6 g/m^2), and the increase in mass for this root fraction over the last 15 years was 22.0%. The mass of recorded coarse roots was 78.6% of their mass in the "control" (1049.1 ± 13.29 g/m^2), and the increase in the mass of coarse roots over the last 15 years was on the order of 25.2%. Within a 50-centimeter layer of soil, the largest mass of fine roots (3.2 times more than on the existing path) was recorded in a 5-10-centimeter soil layer, and coarse roots (1.5 times more) – in the 10-15-centimeter layer of soil.

In the process of restoring the water-physical properties of gray forest soils, the 7-year-old self-seeding *Umus scabra* deserves special attention, which actually significantly contributed to the increase (by 23.2%) of the root mass within this location. Roots of *Ulmus scabra*, inhabiting excessively compacted surface layers of the soil, loosen them, and hyphae of fungi, which settle on fine roots and form mycorrhiza, facilitate access to seedlings of water, nutrients and minerals. In the soil of location 3, at a depth of 5-10 centimetres it's observed vertically directed soil passages formed by earthworms. The passages were mainly grouped in 3-5 pieces and their diameter reached 6 mm.

In particular, common earthworms, in park phytocenoses, provided that bioturbations are involved, such as digging, production of coprolites, mixing of organic materials and mineral particles, can effectively influence both the physical and biological properties of soils. After all, earthworms, penetrating the soil, build burrows that increase the space of cracks, transport organic matter during the production of coprolites, grind organic materials during their decomposition, and also provide plants with nutrients due to their concentration in the walls processes, change the diversity and contribute to the growth of the activity of microbial communities due to the selective consumption of certain groups of microorganisms.

Discussion

Scientific data related to the content of solid particles, air and water in the upper 50-centimeter layer of gray forest soils, as well as their population with the roots of woody and herbaceous plants, have been expanded and clarified by F. Brovko *et al.* (2023). The obtained data on the water properties of gray forest soils clarify and supplement the information on the water-physical properties of brown mountain forest soils (Lenevych, 2020) and sod-layered soils surveyed in the Oleksandria park, which is located near active roots in the soil layer, due to the prevention of its compaction in the stands of woody plants (Dragan, 2012).

For the gray forest soils exposed within the forests of the dendrology park "Oleksandria", there are compaction 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 compaction of 1.46-1.59 g/m^3 – grass cover is absent (Dragan, 2012). According to F. Brovko *et al.* (2023), within the hornbeam groves growing in Holosiivo park, the significant influence of anthropogenic trampling on the compaction of gray forest soils was traced to a depth of 45 cm. At the same time, the maximum rates of soil compaction (38.0% higher than in the control) were characteristic of the upper 0-5 cm layer, and the minimum (4.9%) were observed in the 40-45 cm layer.

Research by P. Teyluk *et al.* (2022) indicates that recreational trampling can lead to changes in the microrelief of territories, which in turn affects the redistribution of moisture. After all, along the paths the soil is compacted and the relief is lowered. A berm is formed along the path, along which water flows during precipitation. This contributes to the development of erosion processes and is manifested in the washing away of soil from its surface, which is also confirmed by our research (Fig. 1b).

Field studies conducted within the examined locations, with different manifestations of the intensity of trampling and compaction of the soil surface, show that the degree of changes in their water and physical properties depends on the combination of individual components of the complex of ecological factors that dominate within the path. At the same time, their manifestation usually occurs due to a violation of the water-air regime of soils, a decrease in porosity and water content in their upper soil layers (Korkanç, 2013).

Research by S.A. Lei (2004) quantitatively investigated the impact of various recreational activities on soil properties in a blackbrush (Coleogyne ramosissima) shrubland. The findings indicated that human trampling, biking, and off-road motor vehicle traffic adversely affect soil properties by compacting the soil, leading to reduced porosity and increased soil penetration resistance. Research confirms the conclusion of O. Lenevych (2020) that within the path, in the absence of anthropogenic influence, the soil that has undergone degradation processes is able to restore its natural state over time.

In particular, the water content in the upper 50-cm layer of gray forest soils, at the time of the study, on the active path was 501.6 ± 7.46 m^3/ha, and on the decommissioned path – 483.9 ± 7.66 m^3/ha. The water content within the 5-centimeter layers of the soil profile differed from its values obtained in the "control". On the path that has been in use for more than 30 years, the difference was 1.5-12.4%, and on the path that was decommissioned 15 years ago, the difference was smaller and was at the level of 1.1-5.6%. However, the obtained values of the Student's criterion (t = 0.2-2.7) indicate the absence of a significant difference between the indicators of water content at the studied locations. The numerical values of the water content (476.2 ± 5.97 - 501.6 ± 7.46 m^3/ha and the coefficients characterizing the saturation of cracks with water 0.13-0.43 units, recorded in the upper layers of the 50-centimeter soil layer, were beyond the optimal values (0.80 units) and indirectly indicated the dependence of their water regime on the presence or absence of atmospheric precipitation, its duration and frequency.

F. Brovko *et al.* (2023) researched that the highest indicators of anthropogenic trampling were observed on the path, which was used as intended for more than 30 years, namely in its upper 10-centimeter layer, where the soil (compared to the location without signs of trampling) had a 32.1-38.0% higher compaction and correspondingly, the content is smaller by the same percentage. The content of solid particles per unit volume of soil was higher by 14.1-22.8%, and the population of the studied layer by fine roots of woody plants was lower by 84.6-91.2%.

The water permeability of the soil, in this layer, had the lowest indicators, because the rate of water filtration was at the level of 18-22 mm/h, which is 90.3-90.6% less than in the control. Under the certain environmental conditions that can cause a threat from the development of erosion processes on the paths, with similar soil compaction. The given data are consistent and do not contradict the data obtained on the path network of the "Boykivshyna" National Nature Park (Lenevych *et al.*, 2023).

The infiltration resistance and water penetration were most sensitive to soil compaction, as also confirmed by studies conducted A. Ferrero & J. Lipiec (2000). They indicated that the decrease in hydraulic properties in the most compacted soils occurred due to lower macroporosity.

It is also worth noting that at the location where a part of the path has been operated for more than 30 years, in the upper 50-cm layer of gray forest soils, the total mass of the roots that populated them was 983.4 ± 3.56 g/m^2, and this is only 40.6% of the total mass of roots recorded at the studied location without signs of trampling. At the same time, the share of fine roots inhabiting this layer of soil was much smaller (23.7%) than coarse roots (54.3%), and their mass was at the level of 257.9 ± 0.45 g/m^2 and 725.5 ± 3.25 g/m^2 respectively. Such ratio between the fractions of the investigated roots, as evidenced by Z.H. Kalahroudi *et al.* (2023) associated with mechanical damage and death of part of fine roots as a result of over-compaction of the upper soil layers.

After the cessation of anthropogenic trampling, the natural processes of restoration of degraded soils, as it happened in our case, at a location where the path has not been used for the past 15 years, begin within the path. The restoration begins with the fall of leaves on the surface of the path and continues thanks to the formation of the forest litter on it, its settlement by self-seeding *Ulmus scabra* and the appearance of earthworms in the surface layer of the soil. Intensification of processes, as noted by

O. Lenevych (2020), occurs in the autumn-winter period, during the greatest fluctuations in the temperature regime on the soil surface and is mostly associated with freezing or thawing of the soil in its upper layers. The changes in the physical properties of the upper 10-cm layer of light gray forest soils after trampling stopped indicate that during the last 15 years, at this location (compared to the part of the path where the soil has been trampled for more than 30 years), there has been an improvement in their quantitative and relative indicators. In particular, as evidenced by F. Brovko *et al.* (2023), there was a decrease in soil compaction (by 16.9-19.5%) and the content of solid particles per unit volume (by 6.2-9.9%), as well as an increase in the percentage of cracks per unit volume of soil (by 23.6-39.1%) and the mass of fine roots of woody plants (by 3.2-3.3 times).

At the location where the path has been trampled for more than 30 years, the upper 10-centimeter soil layer contained 31% of fine roots, compared to their mass recorded in the 50-centimeter soil layer (255 ± 0.4 g/m^2), and at the location where the path was not trodden during the last 15 years, the content of fine roots of woody plants was higher (51%), and their mass in a 50-cm soil layer was 495 ± 5.1 g/m^2. Evaluating the total content of the roots of woody plants in a 50-centimeter layer of soil, at a location where the path has not been trampled for the past 15 years, it should be noted that the total mass of roots exceeded the mass of roots recorded at a location where the soil had been trampled for 30 years by 57.2%, and their mass was 1545.7 ± 11.20 g/m^2. The mass of fine roots prevailed by 92.6% and was at the level of 496.6 ± 5.09 g/m^2, and the mass of coarse roots was greater by 44.6% and was estimated at 1049.1 ± 13.29 g/m^2. The data indicate that the main mass of fine roots of woody plants master the upper 10-centimeter soil layer and do not contradict the quantitative and relative indicators obtained for sod-layered soils (Ryzhov & Brovko 2014).

Thus, at the studied locations, the moisture regime of gray forest soils is formed due to atmospheric precipitation. At the same time, water reserves in the upper 50-centimeter layer of soils under the canopy of the studied stand, both in the cells that were not trampled and within the paths, did not have significant differences, and a significant impact of trampling on the content of solid particles, water, air and roots of woody plants in the soil was traced to a depth of 40 centimeters.

Conclusions

The quantitative indicators of water reserves in the upper 50-cm layer of gray forest soils under the canopy of the studied 90-year-old stand at the three surveyed locations were marked by insignificant differences (Student's criterion t = 0.2-2.7). In particular, at the location without signs of trampling, the water content was observed at the level of 476.2 ± 5.79 m^3/ha, at the location where the path has been used for its purpose for more than 30 years, the water reserves were 5.3% higher, and at the location where the path was removed from operation 15 years ago, the difference was at the level of 1.6%.

The coefficients of water saturation of the cracks in the upper 50-centimeter soil layer were beyond the optimal values (0.80), and significant differences between the obtained coefficients were observed up to a depth of 45 cm. At the location without visible signs of trampling, the coefficients of saturation of cracks with water were within 0.13-0.23 units, and on the exploited path they were 22.2-87.0% higher. At the location where the path has not been exploited for the past 15 years, the difference between the coefficients saturation, in comparison with the first location, was lower and amounted to 16.7-66.7%.

The most intensive water filtration was observed at the location without visible signs of trampling and was 191 ± 5.0 - 226 ± 6.9 mm/h. At the location where the path was in use for more than 30 years, water filtration rates were only 9.4-9.7%, and at the location where the path was decommissioned 15 years ago, water filtration rates were 33.6-40.8% of the rates obtained at the control location.

It was found that under the influence of anthropogenic trampling, there are significant changes in the ratio of solid particles, air and water in their upper 45-centimeter soil layer ($t = 3.0-42.7$), and the lowest content of solid particles (65.0 ± 0.90 - 77.2% ± 0.32 per unit volume of soil), was observed at the first location, without visible signs of trampling of the topsoil. In the second and third locations, where the soils were trampled, the content of solid particles per unit volume of soil was 2.2-22.8% and 1.0-10.6% respectively higher than in the first location.

The largest mass of roots (2423.9 ± 3.79 g/m^2) was observed in the upper 50-cm layer, at the location, without visible signs of trampling of the topsoil. Of their total mass, the fraction of fine roots was 44.9%, and coarse roots – 55.1%.

It's worth continuing research related to the elucidation of the dynamics of natural overgrowth of trampled space with woody and herbaceous plants, as well as the dynamics of restoration of soil density, solid particle content, pores, and roots of vegetation in the studied plantation.

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None.

Conflict of Interest

None.

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Водно-фізичні властивості сірих лісових ґрунтів та їх коренезаселеність в осередках антропогенного витоптування

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Анотація. Метою досліджень стало виявлення впливу антропогенного витоптування сірих лісових ґрунтів на уміст у них вологи, повітря, твердих часток та маси дрібних і грубих коренів. Уміст води і водопроникність ґрунтів визначали за загальноприйнятими методиками, а вміст твердих часток, води і повітря в одиниці об’єму ґрунту – за допомогою мірних циліндрів. Заселення ґрунту коренями визначали методом «монолітів». З’ясовано, що під впливом антропогенного витоптування запаси води у верхньому 50-сантиметровому прошарку ґрунтів були на 1,6-5,3 % більші, ніж під 90-річним дубово-грабовим насадженням без видимих ознак деградації, а коефіцієнт насичення ґрунту водою, під час проведення досліджень, був нижчим (0,21-0,43 %) за оптимальні значення (0,80 %). При цьому, найбільших деградаційних змін досліджені фізичні показники зазнавали у верхній 10-сантимеровій товщі сірих лісових ґрунтів. Тут було зафіксовано збільшення умісту твердих часток ґрунту (на 14,1-22,8 %), а також зменшення об’єму шпарин (на 32,0-44,3 %)

та маси фізіологічно активних коренів деревних рослин (на 84,6-91,2 %). Показано, що у разі припинення витоптування поверхні стежки, природне відновлення деградованих фізичних показників в ущільнених ґрунтах найінтенсивніше відбувається у верхній 5-сантиметровій товщі. При цьому, за 15-річний період, спостерігалися зміни у зменшенні умісту твердих часток (на 9,9 %), збільшенні умісту шпарин (на 39,1 %) та фізіологічно активних коренів деревних рослин (на 330,0 %). Наукова новизна полягає в тому, що отримані кількісні та відносні показники умісту в антропогенно-ущільнених ґрунтах твердих часток, повітря та води пояснюють особливості його заселення коренями деревних і трав’яних рослин, а також свідчать про прикладне значення результатів, представлених у дослідженні

Ключові слова: ущільнення ґрунту; водопроникність; паркові насадження; надземний покрив; заселення ґрунту коріннямвологе середовище; коливання температури та вологості; руйнівне навантаження