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Effects of recreational and residential functional land use on urban soils

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Abstract

Soils in residential areas of cities are heavily degraded, and the environmentally protective and formative functions are instead realized by the soils in recreational areas (city parks, etc.). The study aimed to analyse the influence of functional land use and the level of anthropogenic impact on the properties of anthropogenic horizons (Au and Aτ) in the city of Volgograd, Russia. In this study, we analysed 50 soil samples from the city's recreational and residential functional areas under field and laboratory conditions. The study evaluated the morphological aspects (thickness, colour, structure, and presence of artefacts), physical properties (bulk density, texture), and chemical properties (pH_{water}, salt content, $CaCO_3$, C_{org}, SOC_{stoc}) of the soils. The anthropogenic Au horizons in residential areas exhibited a clumpy structure, numerous artefacts, and significant compaction. Conversely, the soils in recreational zones contained fewer anthropogenic artefacts, with the Aτ horizons characterized by a lumpy structure. The anthropogenic horizons' median and mean property values in the functional zones showed significant differences. The acid-alkaline properties of the studied horizons were weakly alkaline in recreational areas and alkaline in residential areas. A common feature of all anthropogenic horizons was the variability in chemical, physical, and morphological properties depending on the functional zone and level of anthropogenic load. The indicators of a specific level of anthropogenic impact on urban landscapes included horizon thickness, C_{org} content, colour, and structure.

Keywords: soils of recreational areas, residential areas, Technic, Urbic, Technosols, physical and chemical properties of soils

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Introduction

Soil cover in cities is characterized by diversity and heterogeneity, featuring a combination of natural, natural-anthropogenic, and anthropogenic soils. Despite significant changes in morphological, physical, and chemical properties compared to natural horizons, anthropogenic horizons play ecological roles by providing conditions for vegetation growth and enhancing the quality of urban life for the population (Blume, H.P. 1989; Novák, T.J. *et al.* 2020).

A horizons exhibit varying morphological, chemical, and physical properties depending on the functional zone and the level of anthropogenic influence (Pouyat, R.V. *et al.* 2007; Zhevelev, H. and Kutiel, B.P. 2012; De Lucia, B. *et al.* 2013). For instance, soils in transportation, industrial, and residential areas tend to have high density (Zhao, D. *et al.* 2013; Chupina, V.I. 2020). Soil in recreational areas often contains elevated levels of C_{org} (Zhao, D. *et al.* 2013; Charzyński, P. *et al.* 2018). In residential zones, surface sealing and lowering of the water table lead to reduced soil moisture content (Blume, H.P. 1989; Burghardt, W. 2006; Sándor, G. *et al.* 2013). Urban soils become more alkaline due to dust deposits rich in calcium and magnesium carbonates, as well as the use of deicing agents. Additionally, pH levels tend to in-

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crease due to decreased organic matter resulting from reduced vegetation biomass (Brevik, E.C. and Fenton, T.E. 2012; Zhevelev, H.M. *et al.* 2013). Some studies have observed a pH decrease attributed to precipitation acidification (Sukopp, H. *et al.* 1979). The use of heavy machinery in residential areas can cause soil compaction, reduced pore size, and the formation of a clumpy structure (Jim, C. and Ng, Y. 2018). This, in turn, slows down the infiltration of atmospheric moisture, energy transfer, plant growth, aeration, and organic carbon accumulation (Scalenghe, R. and Marsan, F.A. 2009; Jim, C. and Ng, Y. 2018). Consequently, soil structure degradation and a decrease in organic carbon content occur (De Lucia, B. *et al.* 2013).

In general, anthropogenic A horizons exhibit a wide range of properties across most cities worldwide. This variability has been observed in cities such as Zielona Góra in Poland (Greinert, A. 2015), Paris in France (Cambou, A. *et al.* 2018), Rostov-on-Don and Murmansk in Russia (Dvornikov, Y.A. *et al.* 2021), and Ghent in Belgium (Delbecque, N. *et al.* 2022). However, cities like Detroit and New York City in the USA (Howard, J. and Orlicki, K. [2015], and Huot, H. *et al.* [2016]), the Rostov agglomeration in Russia (Bezuglova, O.S. *et al.* 2018), Toruń in Poland (Charzyński, P. *et al.* 2018), Moscow in Russia (Prokof'eva, T. *et al.* 2020), Akure and Okitipupa towns in Nigeria (Adelana, A.O. *et al.* 2023) show similarities in certain properties of anthropogenic horizons across different functional zones, such as pH, thickness, and grain-size composition.

The objective of the study was to analyse the morphological, chemical, and physical properties of anthropogenic soil horizons Au and Aτ in Volgograd city based on the functional land use type and the level of anthropogenic impact.

Hypothesis: The properties of anthropogenic soil horizons will exhibit distinct variations depending on the functional zoning of an urban area, with significant differences between residential and recreational zones. We predict that soil horizons in recreational zones will demonstrate distinctive characteristics compared to those in residential areas, reflecting the specific land use practices and human activities associated with each zoning type.

Materials and methods

Study area

Volgograd, a major industrial city in the Russian Federation, boasts significant industrial and residential capabilities. The town is situated in an area characterized by Cambisols (Protocalcic), Cambisols (Protocalcic, Sodic), and Haplic Kastanozems of varying grain-size compositions. The soils within the city limits have undergone extensive transformation, with residential and industrial areas featuring Urbic Technosols and Ekranic Technosols, while recreational areas include Technosols (Mollic), Hortic Anthrosols, Cambisols (Protocalcic, Technic), and Haplic Kastanozems (Technic) (Gordienko, O. *et al.* 2022), classified according to the World Reference Base for Soil Resources (WRB) (IUSS Working Group, 2022). The primary factor influencing soil formation is anthropogenic.

In the city development plan for Volgograd, residential areas are designated for the construction of residential, public, and industrial structures, along with roads and streets, while recreational zones encompass city parks, squares, and boulevards *(Figure 1)*.

The study focused on the soils of recreational areas and adjacent residential zones, specifically Druzhba Park (48°35′3.53″N, 44°26′31.27″E), Sasha Filippov Park (48°41′42.84″N, 44°29′58.67″E), and the city arboretum (48°38′37.22″N, 44°26′11.06″E). These selected research sites vary in terms of anthropogenic impact and recreational usage yet share similar geomorphological conditions.

In 1943, Volgograd (at that time Stalingrad) was entirely devastated. Reconstruction efforts commenced promptly after the cessation of hostilities in February 1943. The majority of explosion craters, defensive positions, and ruined structures were cleared

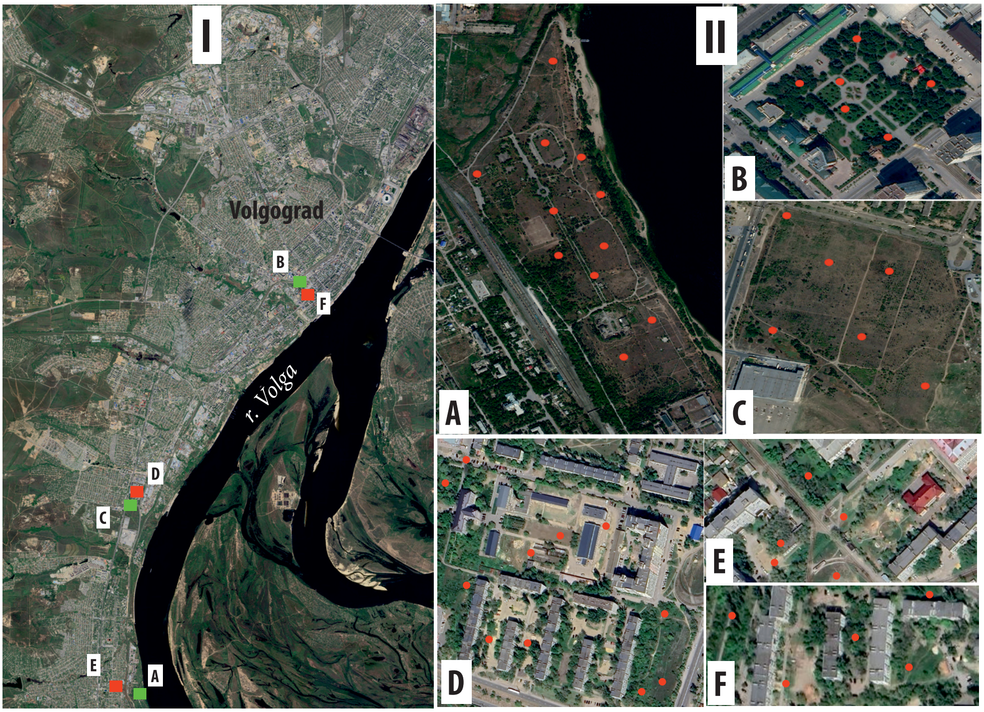

Fig. 1. Map-scheme of research objects. I = Study areas within the boundaries of the urbanized part of the city; II = Study sites in the recreational (A, B, C), and residential (D, E, F) area. *Source*: Authors' own elaboration.

through mechanical means and deposited into nearby gullies. Consequently, soil formation within the city is initiated simultaneously in all zones under uniform conditions.

The study focused on the anthropogenic horizons designated Au and Aτ, as per FAO classification, analogous to Russian urban horizons UR and RAT (FAO, 2006; Prokof'eva, T.V. *et al.* 2017). Despite residential and recreational soils potentially belonging to different Reference Soil Groups, they commonly feature the presence of anthropogenic horizons Au and Aτ.

The anthropogenic horizons were categorized into groups to test the hypothesis regarding variations in properties based on anthropogenic load and functional zones *(Figure 2)*:

Total sampling of A horizons (50 samples), corresponding to the number of soil genetic horizons, including:

1. Aτ (33 samples) from recreational areas,
2. Au (17 samples) from residential areas.

The distinction between Au and Aτ horizons is based on their genesis and artefact volume (%). Au horizons (qualifier Urbic) are predominantly found in residential, industrial, and transport zones, characterized by the introduction of various substrates on the surface, containing ≥ 20 percent artefacts (mainly building and household waste) and often sandy or rocky. Aτ horizons, while similar in origin to Au, contain soil material deliberately transported by humans from outside the immediate environment, with 5–10 percent artefacts, unaffected by natural recycling or movement processes.

Soil properties and indicators such as horizon thickness, structure, colour (based on Munsell scale), bulk density (BD), physical clay content (< 0.01 mm), pH (water), salt content, $CaCO_3$, C_{org} content, and SOC_{stoc} (soil organic carbon stock) were compared and analysed.

Fig. 2. Examples of soil profiles with anthropogenic Au and At horizons in recreational and residential functional zones. *Source*: Authors' own elaboration.

Methods

Soil morphological properties

Between 2022 and 2024, a total of 44 soil sections were laid out and described. Transects were established at depths ranging from 1.5 to 2.0 metres. Each transect underwent morphological description and soil sampling by genetic horizons. The selection of transect locations was influenced by the on-farm zoning of the area, considering factors such as paths, palisades, and inner spaces of residential areas. During fieldwork, soil samples were collected, and their colours were recorded based on the Munsell chart. The soil colour data obtained in the field were used to calculate the soil humus horizon index values, as per the equation:

$$ADI = \frac{HT}{(V \cdot C)} + 1, \quad (1)$$

where *ADI* is the A horizon development index, *HT* is the horizon thickness in cm; *V* stands for value, and *C* stands for colour chroma according to the Munsell chart (Mazurek, R. *et al.* 2016). Soil classification was conducted in accordance with the international soil classification WRB 2022 (IUSS Working Group, 2022). Artefacts were described based on their abundance, size, shape, and fragment nature. The size, abundance, and origin of artefacts were classified per FAO recommendations (FAO, 2006). Sampling was carried out from the horizon's centre (where the expression is most pronounced). If multiple samples were collected from the same horizon, they were taken at balanced intervals.

Soil chemical properties

Samples were collected from each Au horizon of the soil profiles. In the laboratory studies, the following soil indicators were determined:

- Soil pH was measured potentio-metrically in the supernatant suspension of a 1:2.5 soil-to-liquid mixture (water) using the pH-meter-millivoltmeter pH-410 (Van Reeuwijk, L.P. 2002).
- Total salt content was instrumentally determined using the conductometer HI98302 DiST 2 in soil-water extracts at a ratio of 1:5 (Van Reeuwijk, L.P. 2002).
- Soil organic carbon content was assessed following the Nikitin method with a colourimetric endpoint suggested by Orlov-Grindel (Mineev, V.G. 2001).
- Soil organic carbon stock (SOC_{stoc}) for mineral soils was calculated using an equation:

$$SOC_{stoc} = C_{org} \cdot BD \cdot d \cdot CF_{st}, \qquad (2)$$

where C_{org} is the soil organic carbon in percent; BD is the bulk density in g cm^{-3}; d is the depth of the horizon in cm; CF_{st} is the correction factor for stoniness $(CF_{st} = 1 - \frac{\%\,stones}{100})$, including subtraction of gravel and stones (FAO, 2017).

Carbonate content was determined through the metric method, involving the decomposition with a titrated hydrochloric acid solution followed by titration of excess acid with alkali (Arinushkina, E.V. 1962).

Soil physical properties

The soil's particle size distribution (% clay, % silt, % sand) was determined using the Kachinsky pipette method (Kachinsky, N.A. 1958). Bulk density was measured separately using the Cylindrical Core Method for undisturbed samples (98.5 cm^{-3}) (Kachinsky, N.A. 1958).

Statistical processing of data

The results were statistically analysed using the statistical software system R 4.4.0 (Dmitriev, E. 1995). Descriptive statistics were calculated, such as minimum, maximum, mean, and standard deviation. Statistical methods like the Jarque–Bera test, Mann–Whitney U-criterion, and T-criterion were employed. Pearson and Spearman correlation coefficients were used to establish correlation relationships.

The Jarque–Bera ($J–B$) test assessed the normality of data distribution by determining skewness and kurtosis. The test was calculated using a specific formula:

$$J - B = \frac{N}{6} \cdot (Sk^2 + \frac{(K-3)^2}{4}), \qquad (3)$$

where N is the sample volume, Sk is the skewness, K is the kurtosis. If the value of $J–B > 5.991$, it means that the hypothesis of normal distribution of the sample is rejected, i.e., the distribution is non-normal.

After establishing the normality and non-normality of data distribution, tests were performed to check the equality of mean values in two samples (Au and Aτ). The T-criterion was used for the normal distribution of data according to the formula

$$T = \frac{M_1 - M_2}{\sqrt{m_1^2 + m_2^2}}, \qquad (4)$$

where M_1 is the arithmetic mean of the first comparable population (group), M_2 is the arithmetic mean of the second comparable population (group), m_1 is the mean error of the first arithmetic mean, m_2 is the mean error of the second arithmetic mean.

In cases where data were not normally distributed, the Mann–Whitney U-criterion was applied to assess differences between two independent samples. The U-criterion calculation considered sample volumes and rank sums, with lower values indicating more reliable differences in parameter values between samples:

$$U = n_x \cdot n_y + \frac{n(n+1)}{2} - T, \quad (5)$$

where n_x and n_y are sample volumes; n is the sample volume with the larger rank sum; T is the larger sum of ranks from samples X and Y.

Results

The histogram of the generalized data distribution for the thickness of all anthropogenic horizons indicated a lognormal distribution, with values predominantly falling within the range of 10–50 cm (minimum – 3; maximum – 110; median = 24 ± 3 cm). The thickness distribution in recreational and residential areas was described as normal, while the overall sample showed a lognormal distribution *(Figure 3).* In residential areas, the average thickness was 46 ± 7 cm, whereas in recreational areas, it was 18 ± 2 cm.

The structure of the anthropogenic horizons varied from clumpy to lumpy, with differing ratios by zone. Of the total horizons observed, 66 percent exhibited a lumpy structure, while 34 percent displayed a clumpy structure. The distribution of structure types also differed by functional zones: the clumpy structure predominated in residential areas, while the lumpy structure was more prevalent in recreational areas.

The colour of anthropogenic horizons exhibits a range of variations. In residential areas, the colour spans from 2.5YR to 7.5YR, with values between 4 and 6 and chroma ranging from 2 to 4. Conversely, in recreational zones, the colour tends to be darker, typically classified as 10YR with values of 3 to 6 and chroma between 2 and 4.

The A horizon's pH_{water} values exhibited a normal distribution (see *Figure 3*). Across all anthropogenic horizons, pH ranged from 6.6 to 8.5 (mean = 7.9 ± 0.1 cm). Specifically, the pH mean in residential areas was 8.0 ± 0.1 cm, while in recreational areas, it measured 7.7 ± 0.1 cm.

The distribution of salt content values in all anthropogenic horizons followed a lognormal distribution (see *Figure 3*). Overall, the horizons were characterized as non-saline, with a median of 0.12 ± 0.01 percent. Minimal differences were observed between the zones, with a median of 0.12 ± 0.02 percent in the recreational zone and a mean of 0.14 ± 0.02 percent in the residential zone.

The distribution of $CaCO_3$ data in the general sample and recreational area was non-normal, while in the residential area, it was normal (see *Figure 3*). The minimum $CaCO_3$ values differed by 0.4 percent between residential and recreational areas and the maximum by 0.3 percent. The median $CaCO_3$ value for the total sample was 1.3 ± 0.2 percent, while in the recreational zone it was 1.2 ± 0.3 percent. In the residential area, the mean $CaCO_3$ content was 1.7 ± 0.3 percent.

After analysing the histograms of the C_{org} content distribution, it was observed that the data distribution in the general sample and recreational area is non-normal (see *Figure 3*). The C_{org} content in the horizons ranged from 0.3 to 4.9 percent with a median of 1.2 ± 0.03 percent. There were notable variations in this index across zones. Specifically, the mean C_{org} content in the residential zone was 1 ± 0.1 percent, while in the recreational zone, the median was 1.4 ± 0.2 percent. The highest recorded rates were 4.9 percent in the recreational zone and 1.9 percent in the residential zone.

The distribution of SOC_{stoc} data for the total sample displayed leftward asymmetry, as shown in *Figure 3*. In the residential area, the distribution was normal. The generalized SOC_{stoc} values ranged widely from 4 to 168 g kg^{-1}, with a median of 39 ± 6 g kg^{-1}. The mean in the Au horizons was 45 ± 12 g kg^{-1}, while in the Aτ horizons, the median was 34 ± 7 g kg^{-1}.

The distribution of clay content data in all three samples of the A horizon is characterized as normal (see *Figure 3*). The maximum clay content was observed in the residential zone at

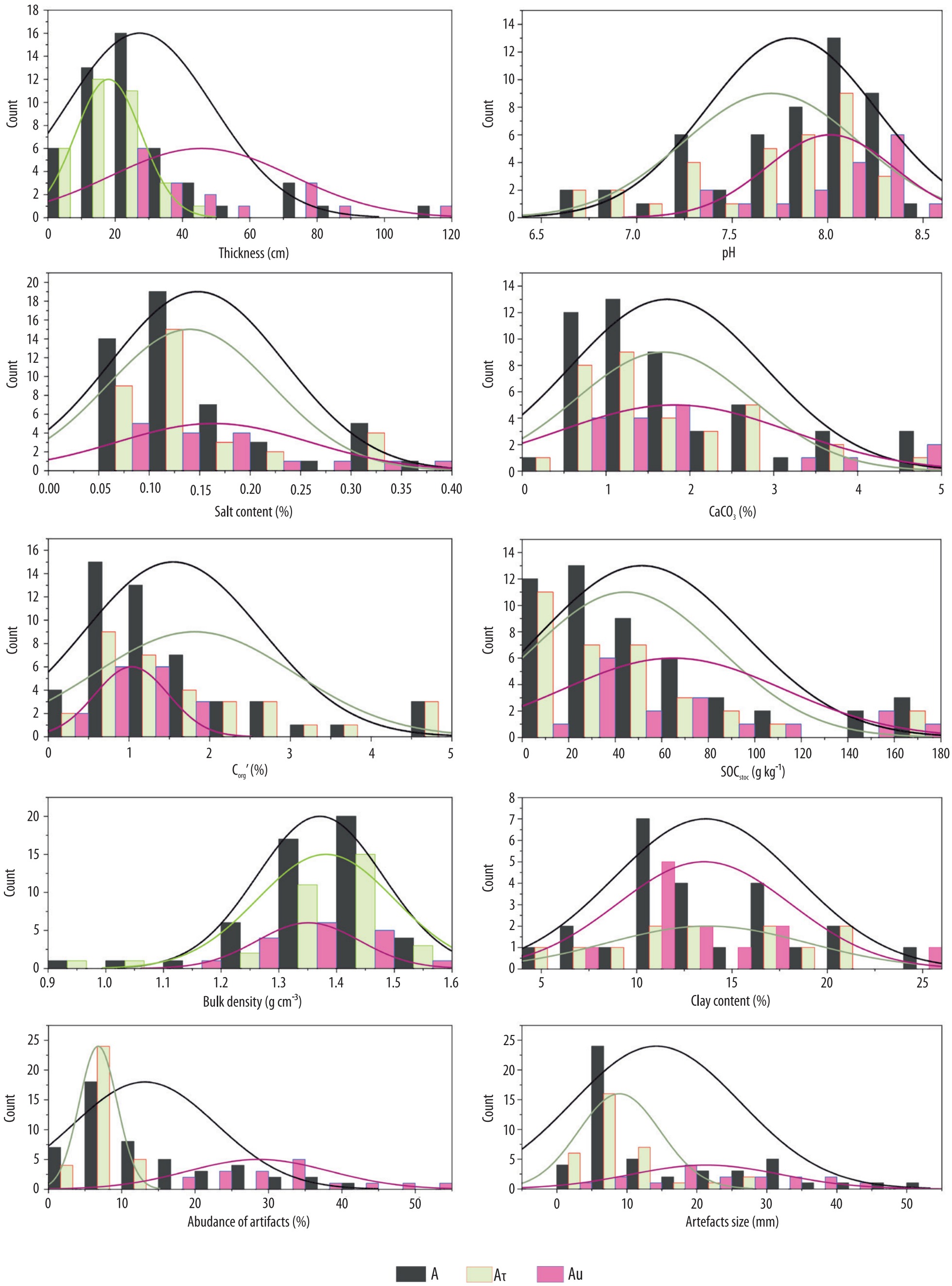

Fig. 3. Distribution of data in anthropogenic horizons of different functional zones. *Source*: Authors' own elaboration.

42 percent, while the minimum was 7 percent in the recreational zone. Notably, high clay content values in the residential areas were sporadic, whereas in recreational areas, the data mainly clustered around 17–25 percent, with some variation from 7 to 38 percent. The predominant clay content range in residential areas was 10–20 percent. Most Au horizons were classified as sandy loam, while Aт horizons were categorized as loam, sandy loam, and loamy sand *(Figure 4)*. The distribution of particular fractions varied across functional zones, with Aт horizons showing dominance in coarse silt and clay along with the sandy fraction. In contrast, residential areas exhibited a prevalence of small and medium sand fractions. The density histogram for all studied horizons displayed a normal distribution (see *Figure 3*), with a mean value of 1.4 ± 0.02 g cm^{-3}.

Discussion and conclusions

Correlation of anthropogenic horizons properties

The greatest differences between the horizons (p-value from 0 to 0.02, at p = 0.05) were found in pH, C_{org}, SOC_{stoc}, and thickness horizons *(Table 1)*. Consequently, these parameters are indicators of the level of anthropogenic load on the territory.

Spearman and Pearson correlation coefficients were used to identify the relationship between soil properties. The non-normal data distribution causes the use of the Spearman coefficient. The result of the J–B test revealed that the distribution of data in the recreational areas obeys a non-normal distribution, except for indicators such as pH, thickness, density, and clay content (see *Table 1*).

In most cases, correlations were absent or weak due to the great heterogeneity of soil properties of all anthropogenic horizons (r < 0.5). Stronger relationships were found between soil density and calcium carbonate content and C_{org}; between calcium carbonate content and C_{org}. As the calcium carbonate content increased, the content of C_{org} and SOC_{stoc} increased. Often, the reverse correlation was observed. For example, when soil density increased, C_{org} and SOC_{stoc} decreased (*Figure 5*, A).

The analysis of the relationship between anthropogenic horizons' chemical and physical properties in different functional zones

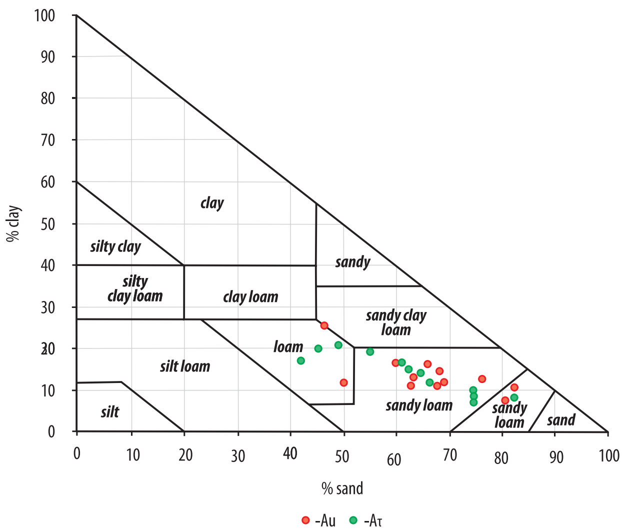

Fig. 4. Texture classes anthropogenic horizons of different functional zones. *Source*: Authors' own elaboration.

Table 1. Variations between Au and Aτ horizons according to Mann–Whitney U-test, T-test, and Jarque–Bera test

Variable	Mann–Whitney U-test	T-test	Jarque–Bera test	
	p-value ≤ 0.05		Aτ	Au
pH_{water}	–	0.02	4.0	2.0
Salt content, %	0.40	–	11.0	5.0
Bulk density, g cm^{-3}	–	0.40	5.5	0.4
$CaCO_3$, %	0.90	–	7.0	5.9
Thickness, cm	–	0.01^{10-3}	2.0	3.0
C_{org}, %	0.02	–	10.0	1.0
SOC_{stoc}, g kg^{-1}	0.08	–	30.0	2.0
Clay, %	–	0.90	1.0	2.0
Abundance of artefacts, %	0.01^{10-3}	–	13.4	6.8
Artefacts size, cm	0.01^{10-3}	–	21.0	10.8

Source: Authors' own elaboration.

revealed that the C_{org} in Au increased with decreasing salt content (r = 0.5) and increasing thickness. The content of calcium carbonates increased with decreasing soil density and increasing horizon thickness. A strong correlation coefficient (r = 0.9) was found between SOC_{stoc} and thickness. Therefore, the higher the Au thickness, the more SOC_{stoc} it contains (*Figure 5*, B).

Similarly, the Aτ horizon properties in recreational zones exhibit similar relationships (*Figure 5*, C). With increasing $CaCO_3$ content, there was an increase in pH (r = 0.5), while C_{org} decreased with increasing density (r = -0.6) and with increasing $CaCO_3$ content (r = 0.6). A correlation was also found between C_{org} content and SOC_{stoc} (r = 0.7).

In conclusion, the statistical analysis indicates that the properties of A horizons show significant variability in chemical, physical (particularly density), and morphological characteristics depending on the functional zone and, consequently, the level of anthropogenic load *(Figure 6).*

Thus, the main types of impact on the residential area were littering and surface sealing. For recreational areas, the anthropogenic impact is reduced due to the special regime of the territory use. Anthropogenic impacts in green areas can include irrigation, the introduction of fertile reclamation mixtures, as well as cleaning the area from domestic and construction waste (Burghardt, W. 2006; Novák, T.J. *et al.* 2020).

Changes in the morphological properties of horizons depending on the anthropogenic load level

Among the morphological indicators, the highest differences were noted in the thickness and structure. The differences were due to the functioning regimes of the territory. In recreational areas with lower anthropogenic impact, the growth of Aτ thickness is sedimentologic, resulting from the slow dust accumulation on the surface (Prokof'eva, T.V. *et al.* 2017). Conversely, in residential areas with higher anthropogenic impact, the growth of horizons is primarily due to the constant addition of new anthropogenic material.

The colour of anthropogenic horizons is directly related to their origin. The products of Au horizons in residential areas are mineral horizons B (Cambic) and Bk (Calcic), as well as soil-forming rocks of loess-like loams and clays (BCk and Ck). As a result, the colour of these horizons is characterized by a light and pale appearance. Conversely, in recreational zones, the colour of the horizons is

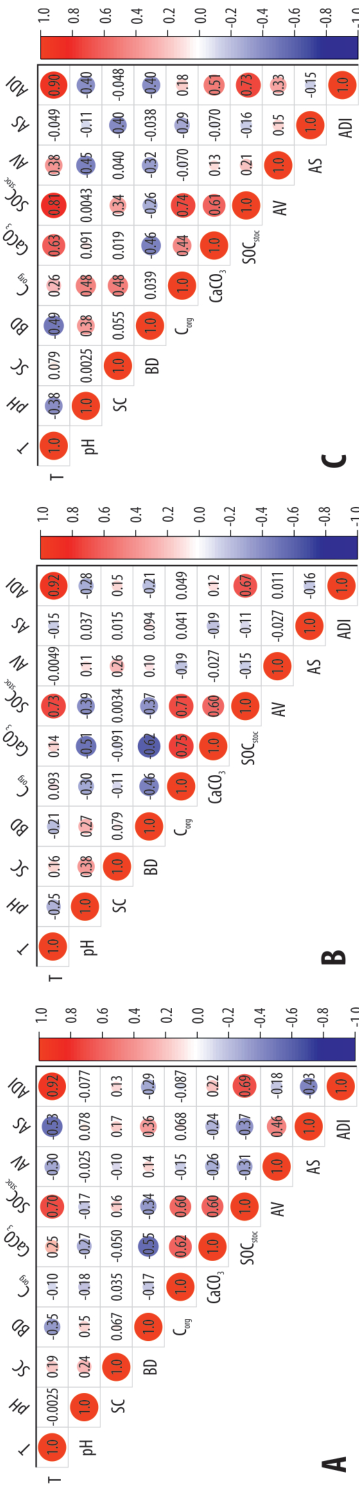

Fig. 5. Correlation coefficients: A = for A (Spearman); B = for Au (Pearson); C = for Aτ horizons (Pearson). T = Thickness, cm; SC = Salt content, %; BD = Bulk density, g cm^{-3}; AV = Abundance of artefacts, %; AS = Artefacts size, cm. *Source:* Authors' own elaboration.

darker and more saturated. In the green areas of Volgograd, Aτ horizons consist of the remains of the original Mollic and Cambic horizons (Kastanozems and Cambisols). The ADI index was calculated to determine the relationship of A horizon colour with other properties. The ADI is based on the horizons' thickness and the value and saturation (chroma) of the wet soil colour. Au horizons are characterized by ADI values ranging from 4 to 15 (median = 6 ± 1.0). In Aτ horizons of recreational zones, the median ADI is 4 ± 0.3 (min – 1, max – 8). Thus, the lighter the horizons are on the Munsell scale, the higher the ADI values. This is supported by the correlations between ADI and SOC_{stoc} (r = -0.67 and r = -0.73), both for the total sample and for horizons in residential and recreational areas. Therefore, the colour of urban soil horizons can be used to assess potential organic matter reserves indirectly.

The structure of the horizons is directly related to human activity. In recreational areas where agronomic techniques such as irrigation and tillage are used, the structure of these Aτ horizons is characterized by lumpy aggregates with rounded sides. On the other hand, in residential areas, the Au horizons are consistently impacted by technogenic factors, resulting in compaction and enlargement of aggregates, leading to the formation of a clumpy structure, exacerbated by moisture deficiency (Gordienko, O. *et al.* 2022).

Artefacts in the Au horizons were predominantly identified in the form of construction, household debris fragments, and metal structures. Their composition significantly varied based on the functional zone. In residential zones, their content ranged from 15 to 50 percent (median = 30 ± 2%), leading to the use of the Urbic qualifier, and in some cases, the additional qualifier Hyperartefactic (layer containing ≥ 50% of artefacts) was applied. Conversely, artefacts in recreational zones were present in smaller quantities – 5 to 10 percent (median = 7 ± 0.5%), making it challenging to classify the soils in this zone as Technosols. Therefore, the additional qualifier Technic (layer containing ≥ 10% of artefacts) was employed. The nature

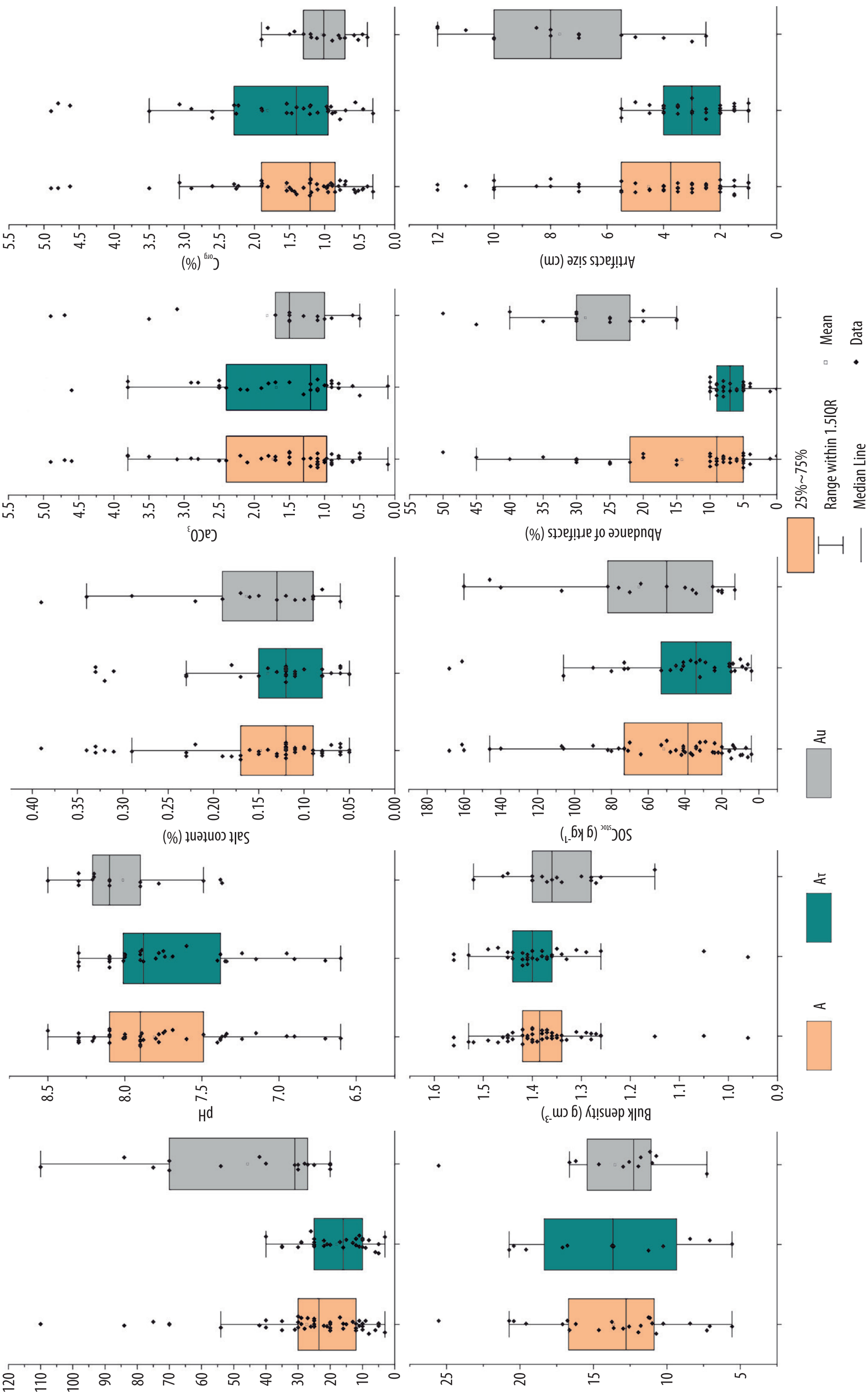

Fig. 6. Variation of properties in anthropogenic horizons. *Source*: Authors' own elaboration.

of artefacts largely depended on the functional zone. In residential areas, artefacts consisted of plastic, glass, and fragments of household and construction debris (such as bricks, concrete, and ceramics). Another significant aspect of artefacts was their size. In the Au horizons, artefact sizes ranged from 2.5 to 12.0 cm (median = 8 ± 1 cm). Artefacts up to 5 cm comprised plastic, glass, and household material fragments, while those exceeding 5 cm were predominantly building materials (such as brick, concrete, and ceramics). In the Aτ horizons, artefact sizes ranged from 1.0 to 6.0 cm (median = 3 ± 1 cm).

Changes in the chemical and physical properties of horizons depend on the anthropogenic load level

The weakly alkaline reaction observed in the Aτ horizons was attributed to the absence of carbonate-containing materials inflow and the leaching process facilitated by irrigation. In residential areas where carbonate inclusions were prevalent, and irrigation was lacking, an increase in $CaCO_3$ content and alkalization was noted. The elevated pH levels in urban soils were likely caused by the release of alkaline substances from calcareous materials (Jim, C. 1998). A similar scenario was observed in urban soils in Hong Kong (China) (Jim, C. 1987; Lam, K-C. *et al.* 2006), in Kumasi (Ghana) (Stow, D.A. *et al.* 2016), in Moscow and Rostov (Russia) (Kasimov, N.S. *et al.* [2016], and Bezuglova, O.S. *et al.* [2018]).

The total salt content in the various Au and Aτ horizons corresponded to the values found in natural horizons of soils in the dry-steppe zone (Kastanozems and Cambisols).

During the morphological description Au horizons in the residential area, it was observed that not only individual structural elements of the soils reacted with a 10 percent HCl solution, but there was also continuous swelling of the soil fine earth. Consequently, active dissolution and redistribution of carbonate inclusions occurred in urban soils (Prokof'eva, T.V. *et al.* 2017). The carbonates in the Au horizons were sourced from the dissolving inclusions of construction debris and dust-aerosol deposition (Kasimov, N.S. *et al.* 2016). This hypothesis is supported by scientific research (Howard, J. and Orlicki, K. 2015; Khalidy, R. *et al.* 2022). In the anthropogenic horizons of Volgograd, no significant correlations between $CaCO_3$ and the volumes and sizes of artefacts were identified. Therefore, it can be inferred that the source of carbonates is the material of the Au horizons. It was previously established that Au horizons in residential zones consisted of B, Bk, BCk, and Ck horizons; hence, the high carbonate values and effervescence from hydrochloric acid were attributed to their mechanical mixing.

The high C_{org} values in the Aτ horizons can be attributed to the systematic introduction of fertile mineral substrates, the optimal water-air regime of soils, and the presence of dense herbaceous, tree, and shrub vegetation, whose decomposition contributes to additional soil carbon accumulation (Vasenev, V.I. and Kuzyakov, Y. 2017; O'Riordan, R. *et al.* 2021). In the residential area, carbon sources may include bituminous-asphalt mixtures, soot, petroleum products, and organic suspended particles (Okolelova, A.A. *et al*. 2021). A direct correlation was observed between the $CaCO_3$ content and the increase in C_{org} content (r = 0.6). Two hypotheses can explain this correlation. The first hypothesis suggests that carbonates do not directly influence the increase in C_{org} since both dust deposition and one-time human inflow can form Au horizons. Therefore, the anthropogenic allochthonous material already contains certain levels of carbonates and C_{org} upon arrival at the surface. According to the second hypothesis, carbonates present in different A horizons within a single profile slow down both the accumulation of C_{org} (from top to bottom of the profile) and its loss to lower horizons due to their bonding properties. The high Ca activity facilitates the fixation of humus by the mineral component of the soil, leading to its retention in the profile through a coagulating effect on soil colloids, including organic matter, thereby inhibiting its migration through the soil profile in solution form.

Infrastructure construction in urban areas results in significant loss of SOC_{stoc} through the removal and displacement of both natural and anthropogenic topsoil and compaction (Elvidge, C.D. *et al.* 2007; Raciti, S.M. *et al.* 2012). In Yixing (China), a correlation between horizon compaction and an increase in SOC_{stoc} was observed (Zhao, D. *et al.* 2013; Wei, Z. *et al.* 2014). However, in our study, the opposite relationship is observed. Greening initiatives notably positively impact SOC_{stoc}, enhancing net primary productivity through urban trees and lawns (Zirkle, G. *et al.* 2011; Nowak, D.J. and Crane, D.E. 2013). Despite similar average densities, the primary factor contributing to the high SOC_{stoc} levels is the average C_{org} values (*Figure 7*, upper) and the thickness of the horizon. The anthropogenic Au horizons are characterized by greater thickness, resulting in higher average SOC_{stoc} levels (*Figure 7*, bottom). It was determined that a high $CaCO_3$ content serves as a source of calcium, promoting mechanisms of flocculation and aggregation of soil particles. This enhances the cementing effect on soil aggregates, improves soil structure, and prolongs the preservation of SOC_{stoc}. This relationship may explain the correlation between SOC_{stoc} and $CaCO_3$ (r = 0.6).

Human activities have resulted in the over-compaction of soil horizons. The high-density values observed in both residential areas (maximum – 1.5 g cm^{-3}) and recreational areas (maximum – 1.6 g cm^{-3}) are primarily attributed to the significant anthropogenic load. The over-compaction of Aτ

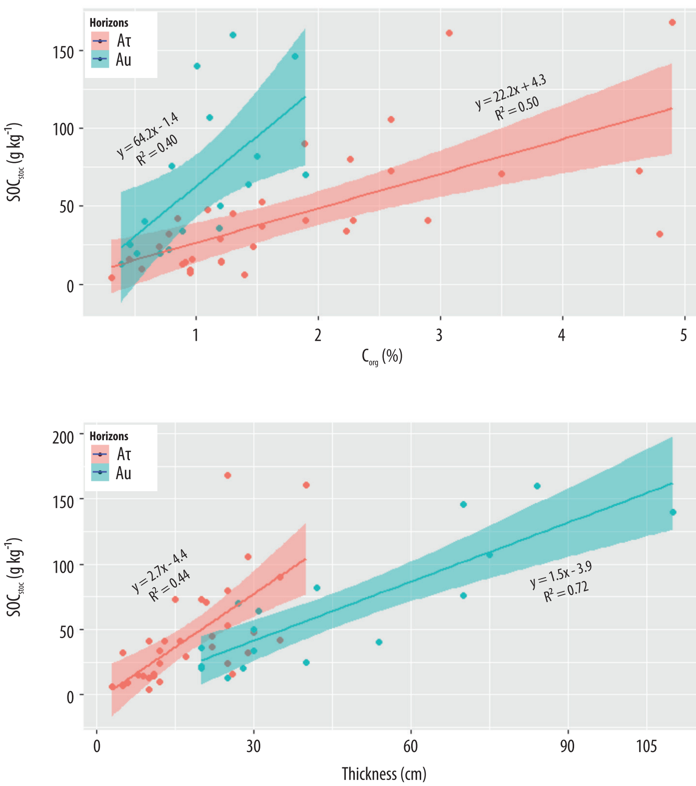

Fig. 7. Relationship between C_{org} and SOC_{stoc} (upper), and between thickness and SOC_{stoc} (bottom). *Source*: Authors' own elaboration.

horizons can be attributed to increased recreational pressure in recreational areas. These findings align with soil density values observed in other cities worldwide, where recreational areas also exhibit increased density (Lorenz, K. and Kandeler, E. 2005). On Au horizons, compaction is induced by transportation activities, construction, and the use of technogenic hard materials for area sealing.

The texture of the Au horizons is characterized as sandy loam. In recreational areas, the introduction of sand through landscaping and reclamation activities alters the texture of Aτ horizons from the loam class to the sandy loam class.

In conclusion, the individual properties such as thickness, C_{org}, and SOC_{stoc} of anthropogenic horizons exhibit significant variability in urban landscapes, challenging the definition of a typical "urban soil." Statistical analysis of data on various properties has enabled the identification of both general trends and distinctive characteristics. The variability of chemical, physical (especially density), and morphological properties based on functional zones and anthropogenic load levels is common. Despite the diverse range of measured properties, correlations between the properties of anthropogenic horizons and land use types have been established. The most significant variations in thickness, stocks, and organic matter content were observed. In residential zones, the thickness varies from 20 to 110 cm, while in recreational zones, it ranges from 3 to 40 cm. The highest C_{org} values were recorded in the recreational zone at 4.9 percent, whereas the lowest was in the residential zone at 0.1 percent. The average SOC_{stoc} in the Au horizons was 45 ± 11.5 g kg^{-1}, with a median of 34 ± 7.0 g kg^{-1} in recreational areas.

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