RESEARCH PAPER



# GIS MAPPING OF THE SOIL COVER OF AN URBANIZED TERRITORY: DRAINAGE BASIN OF THE SETUN RIVER IN THE WEST OF MOSCOW (RUSSIAN FEDERATION)

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ABSTRACT. Soil mapping of urban areas is required for solving many applied problems. However, its methodology is still under development. The lack of information about urban soils and the inconsistence of their classifications are the main difficulties, as well as the intricate soil cover patterns in cities and towns. The research was aimed to compile the soil map for the drainage basin of the small urban river Setun at a scale that could reflect its soil cover heterogeneity. Some new approaches to the differentiation of urban and semi-urban soils in accordance with recent ideas on their systematic and land use variants have been proposed. The concept of pedo-urbo-mosaics, which implements the soil cover pattern theory in relation to urbanized territory, has been used for delineating mapping units. The compilation methodology involved the use of open spatial data and GIS technologies. The subdivision of the basin into mapping units was performed using ©OpenStreetMap data and Yandex Maps Web mapping service. Spatial analysis in GIS allowed for mapping the territory with a moderate urbanization rate on a large scale, obtaining a more adequate and detailed spatial representation of the area than in the case of applying the traditional approach. The map, at a scale of 1:60,000 contains 16 natural/semi-natural soils and technogenic superficial formations, as well as 11 pedo-urbo-mosaics. The study may be of methodological interest as an experience in soil mapping of urbanized areas using GIS.

KEYWORDS: urban soils, soil classification, open spatial data, geoprocessing

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## INTRODUCTION

Mapping of urban areas is a relevant and important sphere of thematic mapping, required for solving applied problems, forecasting, and monitoring both the state of the environment as a whole and individual components of landscapes (Maantay and Ziegler 2006; Makarov et al. 2002), soils, and soil properties in particular (Gerasimova et al. 2003; Van De Vijver et al. 2020). The methodology for mapping the soil cover of cities, towns, and urbanized areas is currently still being formed.

The development of this particular sphere of GIS mapping faces certain difficulties. The amount of specific information concerning urban soils, their properties, and mapping units is insufficient; the very definition of urban soils and their separation from the natural ones depends on the concept of the map compilers (Charzyński and Hulisz 2017a; Prokof'eva et al. 2014). Classifications of urban soils are inconsistent, as they are based on different principles, on the one hand, and are considered as parts of the national basic classification systems, or as a classification of urban soils only, on the other hand (Aparin and Sukhacheva 2015; Burghardt et al. 2022; Charzhyński et al. 2013; Charzhyński et al. 2017b; IUSS Working Group WRB 2022; Lehman and Stahr 2007; Prokof'eva et al. 2014; Stroganova et al. 2005).

Urban landscapes comprise both human-made and natural elements. However, the city is a single spatial system, and its territory should be mapped following the same principles for all soils forming a virtual and spatial continuum from conventionally natural, urban-natural soils to urban soils sensu stricto and technogenic superficial formations (TSFs) perceived as "non-soils" (Tonkonogov 2001; Shishov et al. 2004), but occupying space in towns and cities. Urban-natural soils are those modified by urban impacts and having preserved initial natural properties, as well as soils on technogenic (urban) material with current pedogenesis governed by "natural rules".

*Soils and soil units for urban maps*. Within urban areas, most researchers identify several soil mapping units. Some of them are regarded as actually natural soils, considered background or reference soils. These are soils of green urban infrastructure – protected areas, parks, forests, and gardens (Klimanova and Illarionova 2020). However, in large cities and their suburbs, it seems hardly possible, since such soils are more or less subject to aerial pollution. Furthermore, the soil cover is composed of both undisturbed and slightly disturbed natural soils. Recreational impacts in such areas are insignificant and include compaction of some soils, changes in vegetation, and additions of organic materials, mostly urban waste. Occasionally, local mechanical disturbances can occur in the course of arranging paths, trails, and digging trenches for various cables, as well as due to the construction of infrastructural and sports facilities (Kuznetsov et al. 2017; Paramonova et al. 2010). Therefore, we name such soil mapping units "conventionally natural" soils.

The next (opposite) group includes artificial soils, purposefully constructed for the creation and/or maintenance of green infrastructure (Klimanova and Illarionova 2020; Mankiewicz et al. 2017) or for outdoor sports facilities. Examples of the latter are football fields (Zamotaev and Shevelev 2012), golf courses (Charzyński et al. 2017b), as well as rolled lawns in city parks and boulevards. There are also botanical gardens and even urban vegetable gardens or urban agriculture in cities, where soils are improved – pograded (Lal 2017).

Soils, most typical for the urban environment, were defined in publications as urbanozems (Gerasimova et al. 2003; Stroganova et al. 1998; Stroganova et al. 2005), later urbostratozems (Prokof'eva et al. 2014). They are specified by the presence of urbic diagnostic horizon in their profile. This horizon is composed of natural materials (sands, loams, clay, and fragments of initial soil horizons) mixed with any kind of urban additions (municipal wastes, construction blocks, dust, cultural layer, etc.). The urbic horizon is easily identified by the presence of rather numerous artefacts, and it is growing upward due to the additions of these and similar materials. It may occur either on a buried original soil profile that existed prior to city/town construction, or on the remnants of such profile, or on filled sediments. The name "urbostratozem" was proposed to emphasize additions that form strata and for correlating terminology when adjusting urban soils in the Russian soil classification system (Prokof'eva et al. 2014). In case of a lower thickness of the urbic horizon (< 40 cm) that overlays the identifiable remains of a natural soil, the term "urbo-soil" is used. These remains, mostly middle horizons, permit to identify the original soil and give a name to the urbo-soil, i.e., urbo-soddy-podzolic soil.

Quite special soils are those under highways, roads, squares, parking lots, and courtyards: they are covered or sealed with almost impermeable materials: paving stones, tiles, asphalt, and concrete. Sealed may be initial native soils or their remains, more commonly, special filled grounds – subbase and subgrade layers (sand, gravel) used for drainage, good trafficability, stability of covers and other engineering reasons (Kawahigashi 2017). In all cases, they are more or less strongly isolated from the surface impacts and named ekranozems (Prokof'eva 1998) or Ekranic Technosols (IUSS Working Group WRB 2022).

The non-soils, or technogenic superficial formations, are filled or cut sediments (strata or outcrops, respectively) lacking any genetic soil horizons.

The summarized current knowledge on soils in urban environment is presented in Fig.1.

*Spatial units in cities and towns as identified in the current research.* The intricate land use patterns and high heterogeneity of the soil cover in cities and towns are reasons to substitute the traditional approach to soil mapping with a more adequate one. Instead of delineating areas of individual soils, mapping units with similar compositions of soils – their ingredients – should be shown on the map. They should comprise two-four soils and TSF, if any. Thus, Aparin and Sukhacheva (2014) proposed the idea of "urbopedocombinations within the framework of the urbanized soil space", i.e., combinations, based on the geometry and composition of the polygons (areas) of soils, either natural, or human-modified, with non-soil formations in various proportions. Urban pedological combinations have regular geometric shapes, which distinctly separate them from the areas of almost all natural soils (Aparin and Sukhacheva 2014). Combinations of soils and TSF confined to certain land use zones on the same parent material were named by Shestakov et al. (2013) "urban pedological complexes". Similar concepts can be found in recent publications by foreign authors: pedo-urban complexes (Sobocká et al. 2020), urban pedotopes (Pindral et al. 2020). They were characterized as geographic and cartographic units for displaying the system of abiotic, biotic, and socio-economic components of an urban ecosystem. When identifying mapping units for the soil map of the city of Toruń, Poland, Charzyński and Hulisz (2017a) used the notion of mosaic pattern.

In cities and towns, the shapes of mapping units of almost all ingredients of the soil cover, that is, soil combinations, are determined by anthropogenic factors.

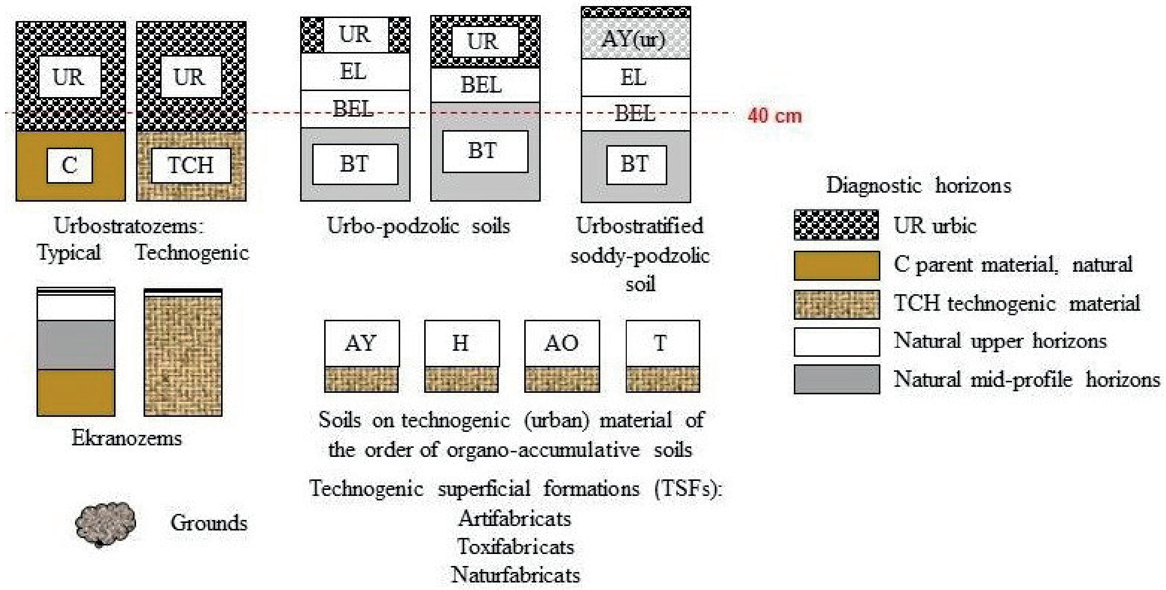


**Fig. 1. Schemes of urban soil profiles within the Setun River drainage basin in terms of soil classification of Russia, with additions by Prokof'eva et al. (2014)**

Consequently, the boundaries between them are usually sharp, irregular or winding, unnatural, and there are no genetic bonds between them. In the theory of soil cover pattern (Fridland, 1972), soil combinations of this type are defined as mosaics, since their components are casual, not related to each other, and quite contrasting. This is exactly how the soil cover in cities is arranged, since its configuration is mostly determined by historical and socio-economic factors, implemented in land use types. Following the criteria for identifying soil combinations in Fridland's theory of soil cover pattern, the soil cover of a city can be defined as composed of *pedo-urbo-mosaics*.

In most projects of large-scale urban soil mapping for delineating the spatial units, remote sensing (RS) data of high spatial resolution were used (for example, Aparin and Sukhacheva 2014; Kulik et al. 2015; Shestakov et al. 2013). For deriving boundaries of pedo-urban complexes, Sobocká et al. (2020, 2021) used open spatial data on land cover/ land use units of the Extended Nomenclature Urban Atlas 2012, which integrates information from different sources, mainly topographic maps and RS data of high and medium spatial resolution (Mapping guide… 2011). The efficiency of using GIS technologies for soil mapping of urban areas is also supported by the possibility of obtaining additional information about soil-forming agents, primarily relief and vegetation, through the analysis of digital terrain models and processing the RS data.

OpenStreetData (OSM), the volunteered spatial database, distributed under the Open Data Commons Open Database License[1], is widely used in large-scale thematic mapping of cities for outlining urban land use categories (Chen et al. 2021; Klimanova et al. 2020; Patriarca et al. 2019), urban greenery (Bobáľová et al. 2024) and classification of local climate zones (Fonte et al. 2019), but for urban soil mapping OSM data are currently undervalued. However, the positional accuracy and quality of OSM data, especially for urban areas, are estimated to be rather high (Borkowska and Pokonieczny 2022; Zheng and Zheng 2014).

The question of selecting the scale for soil maps of urbanized areas remains open. The limited experience in soil mapping of urban areas shows that the relevant cartographic scales for adequately representing the soil cover in cities are 1:25,000-1:75,000, or a larger one (up to 1:5,000) for particular sites of interest (Aparin and Sukhacheva 2014; Charzyński and Hulisz 2017a; Hernandez et al. 2017; Kulik et al. 2015; Shestakov et al. 2013; Sobocká et al. 2020; Vlasov et al. 2017). To our opinion, the most adequate approach for determining the scale of the soil map of urbanized areas is to rely on the average size of the identified soil units, taking into account the standards of traditional soil mapping in Russia in relation to meso- and micro-combinations identified in Fridland's theory of soil cover pattern (Fridland, 1972).

The purpose of this study was to develop methodological approaches to mapping the soil cover of an urbanized area based on GIS technologies, open spatial data, and current concepts on urban soils, as well as to compile the soil map of the urbanized drainage basin of a small urban river.

## MATERIALS AND METHODS

### The study area

The study was performed on the drainage basin of the small urban Setun River, which is the right tributary of the Moskva River. Its catchment area is about 190 km$^2$. There are two urban protected areas in the drainage basin: the Setun River Valley and Tepliy Stan.

The Setun drainage basin is located in the northwestern part of the Teplostan Upland, formed by a protrusion of bedrocks composed of sandy-clay strata from the Jurassic and Lower Cretaceous periods. Bedrocks are overlain by loams, which are underlain by the Dnepr loamy moraine and, less commonly, glaciofluvial sands (State Geological Map 1997). Due to urbanization, the relief has undergone significant changes: ravines and gullies have been filled in, and some parts of the Setun River floodplain have been elevated above the water level by 3-4 m by adding ground. Zonal soils, soddy-podzolics (Albic Retisols), are preserved fragmentarily in green urban areas, although they are somewhat changed by human impact.

Most of the study area is highly urbanized. The density of car roads with high transport intensity is about 2.6 km/km$^2$. There are also several railway lines, the total length of which is about 35 km. The majority of industrial emissions originate from heat and power supply facilities. Among non-industrial sources, facilities related to car repairs, car washes, and tire service, as well as gas stations, predominate (Bityukova and Akynzhanov 2023). Near the river source there is a closed municipal solid waste landfill Salar'yevo, the reclamation of which was implemented in 2018-2020.

The Setun River basin's soil mapping was performed using GIS. The published thematic maps (Ecological atlas of Moscow 2002; Grand comprehensive atlas of Moscow 2012; State Geological Map 1997), and the results of terrain studies have been systematized and organized as a GIS project implemented in the ArcGis™ software. The following OSM standard layers have been used for extracting information about land use and city infrastructure: 'highway-line', 'landuse-polygon', 'building-polygon', 'water-polygon', 'water-line', 'railway-line'. The relief features were analysed through morphometric indicators (slopes, Topographic Wetness Index (TWI)) calculated from the digital elevation model ALOS DEM.

To delineate arboreous/grass vegetation in green urban areas and to assess anthropogenic impact on greenery, as well as to estimate the degree of sealing in urban mapping units, two radiometric indices, the normalized difference vegetation index NDVI (Rouse et al. 1973), and the normalized built-up index NDBI (Chen et al. 2020; Zha et al. 2003), have been calculated for the Sentinel-2A scene (August 2021). The formulas for calculating indices are NDVI = (NIR-R)/(NIR+R), NDBI = (SWIR1-R)/(SWIR1+R), where R, NIR, and SWIR refer to Sentinel bands 4, 8, and 11, respectively. The resulting images had a spatial resolution of 10 m.

The history of land use, mainly on wastelands (unused sites with patches of grasses), was reconstructed using the 1979 Hexagon image and old maps, as well as available satellite data for previous decades.

Terrain research comprised special studies of soils for mapping, both conventionally natural ones and urban soils, in 2019-2022 – morphological descriptions of 46 soil profiles; analytical parameters: soil texture, pH, and organic carbon content of the upper soil horizons were measured at 105 sampling points. Auxiliary materials, that is, field descriptions of 38 soil pits made within the framework of student soil-geochemical training in the Faculty of Geography of Moscow State University in 2020-2021 were used, as well as published data on soils of the area (Prokof'eva and Gerasimova 2018; Prokof'eva et. al. 2020).

[1] https://www.openstreetmap.org

## RESULTS AND DISCUSSION

*Compilation of the soil map.* Since the study has been oriented on methodological issues, its main result comprised the consecutive procedures applied and the map as an example of their application (Figs. 2 and 3). The compilation included two major processing stages: the subdivision of the drainage basin into spatial mapping units (SMUs) using geoprocessing and operations of spatial analysis in GIS, and defining soil units (SUs). Outlines of spatial mapping units are relevant for 2022; their dimensions correspond to a cartographic scale of 1:60,000. To characterize the predominant land use in city blocks, units of multi-storey, middle-storey and low-rise residential areas, as well as administrative, commercial, and business blocks, industrial zones, construction sites, etc., were identified.

The interpretation of open surface areas in the Setun River drainage basin in terms of soils occurring there was based on the knowledge gained in recent years on urban soils (Fig. 1), on the descriptions of soil pits available and supplied with some analytical data, and on the data from the auxiliary GIS layers (georeferenced published maps, remote sensing data, morphometric indicators derived from the ALOS DEM).

Spatial mapping units, except ekranozems and TSFs of construction sites and Salar'yevo landfill (non-soils), were grouped into homogeneous and heterogeneous units (Fig. 2). Almost all homogeneous SMUs, which are sites where the only land use type predominates, correspond to green urban spaces. Limited and diverse field data were the reasons for separating non-disturbed and weakly disturbed soils. Naming urban soils was performed mainly

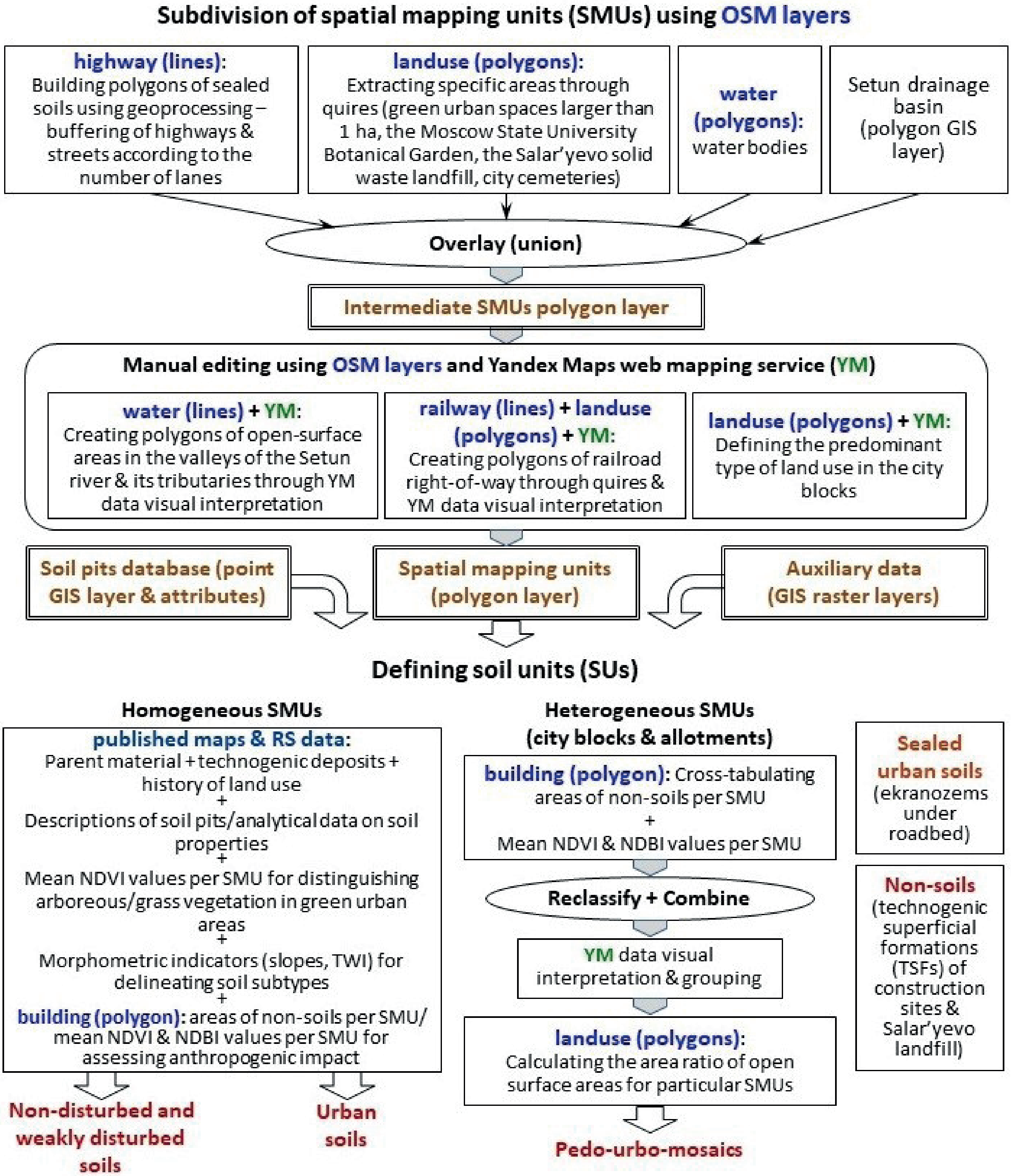


**Fig. 2. Sequence of compilation procedures. Auxiliary data: georeferenced published maps[2], Sentinel-2A scene, ALOS DEM. OSM layers are highlighted in blue, Yandex Maps data - in green. Geoprocessing operations are shown as ovals**

[2] http://www.etomesto.ru

through interpreting the history of land use and the map of technogenic deposits (Grand comprehensive atlas of Moscow 2012). Grassy areas/wastelands were compared with the corresponding sites on the 1979 Hexagon image and other historic images to distinguish between non-disturbed gray-humus (soddy) soils, and postagrogenic and postindustrial (gray-humus (soddy) soils on technogenic material). Slopes and the Topographic Wetness Index (TWI, calculated in SAGA GIS) were used for delineating different subtypes of conventionally natural soils. Therefore, areas with gradients greater than five degrees were interpreted as gray-humus (soddy) soils. Spaces with large TWI values were considered as sites with moisture accumulation and were qualified for soddy-podzolic gleyic and gleyed soils.

City blocks and allotments were considered as heterogeneous units with various combinations of urban soils and non-soils (areas under buildings). The proportion of areas under buildings was calculated using cross-tabulating areas in GIS. Commercial and administrative districts, as well as industrial zones, are built up to the greatest extent – on average, about 17-18%; up to a maximum of 55% of the territory is under buildings and facilities. In residential blocks, the share of land under buildings averages about 16%, with a maximum of 35-40%. In suburban areas with low-rise buildings, approximately 5% of the territory is built up.

*Soil cover.* The soil map (Fig. 3) demonstrates a prominent mosaic pattern of the soil cover in the Setun River drainage basin. The majority of mapping units are of similar size, about 10-20 ha, and almost all of them have a strict geometric shape with curved boundaries, sharp angles, and direct lines. The imprint of urbanization on the soil cover is manifested by the broad ratio of urban mosaics to conventionally homogeneous soils, whose largest areas are composed of zonal soddy-podzolic soils. They occur under green urban areas all over the basin, although they are more common in its western part, and they have some human-produced features. These are artefacts on the soil surface, such as single pieces of urban garbage, fragments of construction materials, either wood, or concrete, fireplaces; the soil surface is sometimes distorted, forest litter may be destroyed, and layers or piles of alien urban material may be spread over the soil surface. Such mapping units are named "soddy-podzolic urbostratified and surficially turbated". The intensity of anthropogenic impact on forests and forest parks was additionally assessed by the differences in the average NDBI values for the relevant mapping units. Interpretation of differences reflects the V-I-S (vegetation-impervious surface-soil) conceptual model for mixed pixels of urban areas (Ridd 1995). Higher average NDBI values, indicating a certain proportion of impervious surfaces, may be considered as a sign of recreational activities: the presence of buildings, walking paths, playgrounds, and sports grounds with an artificial cover. The only Podushkinskyi forest (northwest of the basin) has the least changed soddy-podzolic soils.

Conventionally, natural and semi-natural soils occur in very small mapping units in some sections of the Setun River and its tributary valleys, except for areas under arboreal vegetation.They are confined to better drained sites, – humus-alluvial soils, and to weakly drained ones, depressions, and/or places with high ground water table, – mucky alluvial gleyic and gleyed soils. One more group of soils forming homogeneous units are gray-humus (soddy) soils on steep slopes, rather old sediments overgrown with grasses, or on any technogenic materials, as well as on old artificial lawns.

Non-disturbed and weakly disturbed soils of green urban spaces occupy 27.8% of the drainage basin, urban soils in homogeneous spatial units (except ekranozems under roadbed with 6.5%) – 5.2% of the mapping area.

The rest of the area, composed of diverse city blocks where unbuilt areas alternate with buildings, is pedo-urbo-mosaics. Eleven types of such mosaics were specified in accordance with the participation of semi-natural and urban soils, as well as technogenic superficial formations. In low-rise residential areas, semi-natural soils (soddy-podzolic urbostratified and surficially turbated and

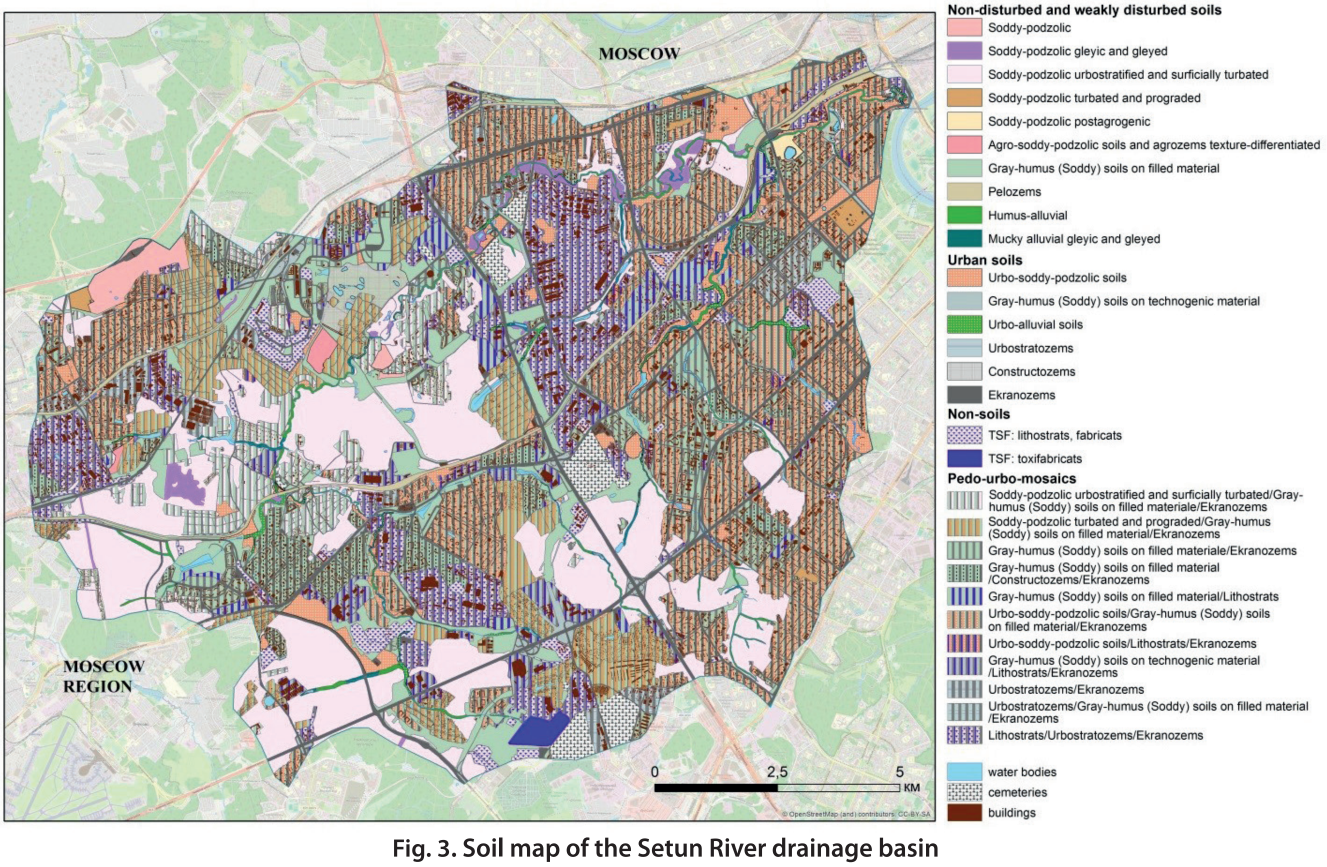


**Fig. 3. Soil map of the Setun River drainage basin**

soddy-podzolic turbated and prograded) alternate with ekranozems. Mosaics for multi-storey, middle-storey, and administrative spatial units include mainly urbo-soddy-podzolic, gray-humus (soddy) soils, and ekranozems, with a significant ratio of constructozems in newly built quarters. Pedo-urbo-mosaics of industrial and commercial areas comprise urbostratozems, lithostrats, gray-humus (soddy) soils on technogenic material, and ekranozems (Fig. 3).

Using the 'landuse-polygon' OSM layer allowed for estimating spatial ratios of open surface soils and non-soils in different pedo-urbo-mosaics. For example, in pedo-urbo-mosaic of multi-storey and middle-storey units, urbo-soddy-podzolic, gray-humus (soddy) soils, and ekranozems occupy 50-65, 5-10, and 10-15%, respectively. In administrative spatial units, this ratio is 30-35, 5-10, and 25-30%, respectively. The rest are non-soils under buildings.

The share of pedo-urbo mosaics in the drainage basin is 55.8%. This ratio agrees well with the area occupied by city blocks and allotments with residential, administrative, and industrial land use type, defined when analyzing heterogeneous SMUs – 34, 9, and 11% of the territory, respectively. The rest of the drainage basin is under TSFs and other objects (water bodies, cemeteries) – 2.4 and 2.3% of the area, respectively.

*Comparison with the soil maps of other cities.* The proposed methodology for compiling soil maps of urbanized areas using open spatial data and GIS-technologies is in good agreement with the approaches proposed in the works of Aparin and Sukhacheva (2014); Charzyński and Hulisz (2017a); Kulik et al. (2015); Shestakov et al. (2013); Sobocká et al. (2020). Similar to these studies, the determining factors in soil units' identification were land use types and transformations of the soil cover in the course of city development. We mapped the heterogeneous soil cover of built-up areas as soil combinations rather than as individual soil units. In addition to detailed remote sensing data, open-source spatial database OSM data were used, which made it possible to specify the structure of land use in urban areas and quantify the ratio of areas under different soils and non-soils in combinations, named pedo-urbo-mosaics. The proposed concept of pedo-urbo-mosaics, derived from Fridland's theory of soil cover pattern, develops the concept of urbopedocombinations used by Aparin and Sukhacheva (2014).

Remote sensing data of medium spatial resolution, similar to those used in our study, was mostly applied for assessing the degree of urbanized territory sealing (Chen et al. 2020; Gordienko et al. 2019). The methodology we propose involves the use of radiometric indices calculated from RS data of medium spatial resolution to assess the degree of anthropogenic impact on soils, primarily in green urban areas. Similar to the above-mentioned studies (Aparin and Sukhacheva 2014; Kulik et al. 2015); Shestakov et al. 2013; Sobocká et al. 2020), we included data on relief. However, we used digital elevation model (DEM), not a topography map, which simplified the use of these data in GIS. The use of auxiliary GIS data (RS and DEM) made it possible, despite the limited field data, to increase reliability when dividing soils into conventionally natural and urban ones as well as to identify variants of conventionally natural and semi-urban soils.

## CONCLUSIONS

Soil mapping of urban areas, which has important applied significance, faces certain difficulties. The low efficiency of detailed soil surveys in urban areas, owing to their significant spatial heterogeneity in terms of soil profile composition and soil properties, the high costs of terrain and laboratory research, as well as the particularities of land use in cities, requires using non-traditional approaches to compiling maps of the soil cover in cities and towns. For mapping, we propose to integrate open spatial data and various predictors (published maps, processed remote sensing data, and digital elevation models) in GIS, similar to approaches used in digital soil mapping (DSM) of natural soils. However, the direct use of DSM procedures to predict soil units in urban areas is not possible since the heterogeneity of the soil cover in city blocks, in combination with the rather homogeneous soil cover of green urban spaces, limits the application of a single mathematical model describing relationships among predictors for the mapping area.

The soil map of the Setun drainage basin at a scale of 1:60,000 has been compiled that allows to use it to solve many applied problems in integrated environmental research. The proposed methodological approaches to mapping the soil cover of an urbanized area based on GIS technologies, open spatial data, and current concepts on urban soils allowed for mapping an area with a moderate level of urbanization at a large scale, obtaining a more adequate and detailed its spatial representation than in the case of applying the traditional approach.

The concept of pedo-urbo-mosaics, implemented in accordance with the soil cover pattern theory, promotes the development of the methodology for mapping urban soils. One more new trend implemented in this work was the differentiation of urban and semi-urban soils in accordance with recent ideas on their classification and land use variants. ■

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