RESEARCH PAPER

URBAN GREEN INFRASTRUCTURE ASSESSMENT: IDENTIFICATION OF PUBLIC GREEN SPACES MISUSE

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ABSTRACT. Assessment of urban green infrastructure is a task of strategic planning and tactical implementation of decisions taken in the context of sustainable development of urban territories. One of the directions of such an assessment is to identify instances of land misuse within cities' public green areas. It reflects the legal fairness of the use of urban green spaces, but currently has a weak scientific justification. Therefore, it is pertinent to develop a methodology for evaluating urban green infrastructure in order to pinpoint areas with inappropriate usage Critical analysis and synthesis allowed us to justify the assessment of the misuse of land within urban green zones as an equal element of the urban green infrastructure assessment system. A geospatial database was created to assess public green spaces. Using the results of remote sensing of territories, as well as the «boxplot» method in combination with the Python programming, the NDVI was calculated, and a classification of vegetation elements and artificial objects located within public green spaces in cities was carried out. Based on the obtained classification categories, a mechanism for identifying «green» areas with misuse of land was proposed, and a list of public green areas with similar violations in St. Petersburg was determined. The practical results of the study include: technology for assessing urban green infrastructure to identify public green spaces with misuse; geospatial databases of public green spaces for St. Petersburg; identified public green spaces with obvious violations of their use, including unauthorized parking, littering, sand dumps, unauthorized placement of industrial, warehouse, retail, transport, or other non-recreational facilities within the boundaries of PGS, vehicle collisions with «green» areas; erroneous inclusion of residential buildings and adjacent courtyards, non-residential facilities, as well as organized parking spaces within PGS's boundaries.

KEYWORDS: greening, territory assessment, sustainable development, misuse of land, boxplot, NDVI, GIS

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INTRODUCTION

Urban green spaces (UGS) are a natural and ecological basis of urbanized areas, play a key role in the formation of a sustainable environment, and perform a number of significant functions: ecological, which includes environment-forming, sanitary-hygienic, environmental, protective (barrier); aesthetic, including decorative and architectural; recreational; transit; specialized; engineering and technical (Ma et al. 2019; Vidal et al. 2022; Jian and Yang 2024). UGS ecosystem services, as a consequence of these functions, provoke socio-economic transformations of the urban environment (Gagarina 2023). For example, the availability and quality of UGS affect the value of real estate in cities by increasing the attractiveness and psychological comfort of territories, reducing noise pollution, and improving the microclimate (Bykowa et.al. 2024). Assessing the potential of multifunctional green infrastructure is an crucial strategic task for environmental protection, socio-economic development, and spatial planning in the region , considering the concept of sustainable development (Cherepovitsyn et al. 2021), an integrated ecosystem approach, and the promotion of social and environmental justice (Enssle and Kabisch 2020; Klimanova et al. 2022; Skachkova and Guryeva 2023).

The global community's experience in assessing UGS is extensive and relates to the various ecosystem services provided by green spaces. Several enlarged groups can help identify the main areas of urban green infrastructure assessment.

UGS spatial accessibility

To assess the quality of public green spaces, taking into account spatial differentiation, Stessens et al. developed a GIS-based proximity sub-model based on the concept of theoretical functional levels (TFL), as well as a quality model based on the example of Brussels (Stessens et al. 2017). The authors understand classification by theoretical functional levels, where green spaces of a certain size have a specific radius of attraction for the population. Together, these models make it possible to assess which TFLs and what level of green space quality is available to residents of each city block in Brussels.

Schindler et al. used a survey of respondents in Brussels, Luxembourg, and Rouen to create models of the spatial movement of respondents from their place of residence to their preferred urban green space. Models are classified as centrifugal and centripetal based on their type of use. It is also concluded that the size of UGS has little effect on the distance respondents travel to them. Accordingly, the size of the landscaping does not affect the choice of a recreation place by residents. Residents can travel to the popular UGS not the standard distance of 300-500 m but 1.4-1.9 km (Schindler et al. 2022). Work by Jang et al. is devoted to the development of an index of urban green spaces accessibility, which shows the features of the green spaces' distribution at the citywide or local level (Jang et al. 2020).

Many researchers write in their publications about the well-known "3-30-300" concept (Schindler et al. 2022; Rakhmatullina et al. 2023; Browning et al. 2024), which provides three rules. Firstly, every resident should be able to see at least three trees from their home. This fact has a positive impact on mental health and well-being. Secondly, every urban area must have 30 percent tree canopy coverage. Barcelona, Bristol, Seattle, Canberra, and Vancouver, for example, set this goal for themselves[1]. Thirdly, a maximum distance of 300 m to the nearest green area must be maintained. This distance appears in many studies (Rakhmatullina et al. 2023; Bolkaner and Asilsoy 2023). Russian legislation normalizes the radius of public green area accessibility: for multi-storey residential buildings, 400 m; for low-rise residential buildings, 800 m (Set of rules 476.1325800.2020). These indicators correspond to a time interval of 5-10 minutes and correlate with the Chinese concept of "city in 15 minutes", "city in 10 minutes" and "city in 5 minutes" (Luo et al. 2022).

Residents' provision of UGS

Usually, the green spaces provision of the population, including public green spaces, is characterized by the "green area per inhabitant" indicator (Grunewald et al. 2019). The World Health Organization defines the maximum parameters for the green space provision per person: the minimum value is 9 m^2, the optimal value is 50 m^2. However, green space provision varies greatly across countries. For example, in Belgium, Australia, and Germany the provision reaches 200 m^2 per person, while for Spain and Macedonia the indicator is only 4 m^2 (Pouya and Aghlmand 2022). For Russian cities, minimum standards for providing green space to the population have been established. For St. Petersburg, these parameters vary from 6 to 18 m^2 depending on the administrative region.

This direction of urban green infrastructure assessment has a qualitative component and may include alternative studies in various aspects: studying the relationship between the green space amount and the mental well-being of children of different ethnicities (McEachan et al. 2018), as well as indicators of the residents' health (general poor health, depression, severe mental illness, etc.) (Mears et al. 2020).

Assessment of the ecological state of green spaces

Assessment of the ecological state of the urban environment includes studies of soil and vegetation cover. Cover is "an integral indicator of environmental well-being and at the same time a potential source of secondary pollution of the natural environment" (Pashkevich et al. 2020; Mityakova et al. 2023). During this assessment, an individual assessment of trees can be carried out according to a set of dendrometric indicators on trial plots; the state of different types of vegetation (trees, shrubs, flower beds, lawns) is determined, as well as a score (coefficient, category) of the ecological state of public green spaces (Shchasnaya and Rondak 2024). The remote sensing approach is also popular for assessing the environmental quality of cities. Giofandi et al. used four indices (NDBI - Build-up Index, NDSI - Soil Index, SAVI - Vegetation Index, NDNI - Moisture Index) and revealed an environmental quality decrease of Pekanbaru city (Riau province, Indonesia) (Giofandi et al. 2024).

Environmental inequality assessment

The concept of environmental justice asserts that all people have the right to benefit from the UGS barrier function (e.g., protection from noise, vibration, pollution) as well as other UGS ecosystem services. Environmental inequality refers to the link between environmental quality and social class divisions. Environmental stratification suggests an uneven distribution of UGS among urban residents. At the same time, the UGS quality varies depending on the socioeconomic status of residents, which means that areas with high incomes tend to have higher qualitative and quantitative indicators of greening (Luo et al. 2022; Wang et al. 2021; Kurniawan 2023). A study by Nesbitt et al. in this area also shows that, in addition to population income, a strong correlation is observed between the presence of higher education among residents and the distribution of urban vegetation (Nesbitt et al. 2019).

However, the results of Chinese colleagues are discordant with the above conclusions, saying that "the provision of green space does not strongly discriminate against people's socioeconomic levels in China". High levels of vegetation quality may apply to different social groups (including migrants and marginalized groups) (Wu et al. 2022). Tehran Research (Iran) shows an intermediate result: areas with higher socioeconomic status in Tehran receive more ecosystem services from UGS. However, in underdeveloped areas, a similar trend is observed (Roodsari and Hoseini 2022). The Paris study is devoted to the relationship between social inequality and the availability of green spaces using the example of Paris (Ile-de-France region). Again, this is an environmental justice concept that raises the issue that in many cities, access to green space is stratified by income and ethnicity (Liotta et al. 2020).

Aesthetic assessment of green spaces (assessment of attractiveness / comfort)

This type of assessment can be carried out in different directions. Brindley et al. consider the cleanliness of greenspace. Their unsatisfactory level negatively has a negative impact on the health of nearby residents. The authors see possible reasons for this in psychological discomfort, which prevents people to visit green spaces and to receive required ecosystem services (Brindley et al. 2019). Stessens et al. investigate the biological value, land cover composition, area, and form of green spaces as key indicators of the quality of public green spaces (PGS), a measure of visitor perception. How people perceive green spaces and their quality is relevant for urban area management purposes (Stessens et al. 2020).

The above list of assessment aspects is not exhaustive. For example, Kuklina et al. assessed green spaces according

[1] C. Konijnendijk van den Bosch (2021). Promoting health and wellbeing through urban forests – Introducing the 3-30-300 rule. [online] The IUCN Urban Alliance. Available at: https://iucnurbanalliance.org/promoting-health-and-wellbeing-through-urban-forests-introducing-the-3-30-300-rule/

to the criterion of urban sustainability in the Arctic (Nadym, Russia) (Kuklina et al. 2021). The Klimanova's study includes the assessment of ecosystem services (Klimanova et al. 2021). In particular, the ecosystem service associated with air purification, taking into account the absorption capacity of trees by a method developed for cities in Canada and America using the iTree tool, is of interest (Nowak et al. 2018). Works devoted to urban heat islands are also related to the assessment of urban infrastructure from the point of view of microclimate regulation by UGS (Kirschner et al. 2023; Murtinová et al. 2024; Pan et al. 2023).

Our study contributes to assessments related to the legal regime of the public green areas used in cities. The misuse placement of objects in public green areas that do not comply with legally established regulations and requirements forcibly reduces urban "green zones". The issue of their preservation, as noted by Klimanova, "is a hot topic among decision-makers and citizens in the largest cities" (Klimanova et al. 2021). It is extremely important that "gray" spaces, which include "anthropogenic, sealed, non-permeable, paved surfaces made of asphalt, concrete, and other durable materials", did not suppress "green" and "blue" spaces in the urbanization processes (Noszczyk 2023).

Unfortunately, there are very few scientific works devoted to the assessment of misuse of public green spaces in cities. These studies are often associated with socio-legal research. A particular example is "green" criminology, which raises issues of environmental damage due to criminal actions of citizens, companies, authorities and their representatives. The "green crime" reason is the desire to achieve economic gain, as well as the undeveloped environmental consciousness of citizens (Ignjatović 2023).

According to Russian legal practice the following violations as typical of the green infrastructure use regime: illegal formation and disposal of land plots; illegal construction; illegal extraction of natural resources. Often, these violations are recorded in the field of use and protection of specially protected natural areas (Berdinskikh 2021). Environmental prosecutors identify more than 3,000 violations in protected areas' territories every year. Government and administrative bodies, as well as citizens and legal entities, violate the law. (Solovyeva et al. 2020). For example, at present (2024), the Russian Investigative Committee is conducting a procedural check regarding the illegal construction of a large sports facility on the territory of the landscape park "Krylatskie Hills" (part of the regional specially protected natural area "Natural and Historical Park "Moskvoretsky", Moscow)[2]. In 2017, a criminal case was opened in St. Petersburg regarding illegal construction on the territory of the Gladyshevsky nature reserve[3]. Unauthorized construction of a cottage village was discovered on the territory of the state natural landscape reserve "Baidarsky" (Rezervnoye village, Sevastopol)[4]. Unfortunately, there are many similar examples throughout Russia. Moreover, such actions lead to both the degradation of the ecosystem and the inability of the green infrastructure to perform ecosystem functions. In particular, illegal actions lead to limited physical access to those green areas that are public by status and, accordingly, have open access. PGS may also be inaccessible due to erroneous decisions made by officials, as well as insufficient social support for the preservation of green spaces (Biernacka and Kronenberg 2019).

To suppress violations related to the organization of unauthorized parking in green areas, control and supervisory measures are carried out in Russia (as part of municipal control in the field of improvement in accordance with the Federal Law of July 31, 2020 No 248-FZ "On State Control (Supervision) and Municipal Control in Russian federation"). These events, which take the form of raids and on-site inspections, involve the examination of the planned territory. The choice of the survey area may be planned or justified by residents' complaints. However, the residents do not always have an active civil legal position, so control and supervisory measures may not be comprehensive and may not reflect the full scale of the problem. Accordingly, it is necessary to introduce additional technologies that allow automatic or semi-automatic assessment of the urban area and then carry out a control and surveillance raid. Spiridonov notes that promising ways to improve control and supervisory activities are the introduction of remote control technologies using services that allow "to use modern digitalization achievements to increase the efficiency and convenience of practical control (supervision)" (Spiridonov 2023). For complex spatiotemporal analysis, it is necessary to use modern geographic information systems, among which QGIS is currently the leader (Stessens et al. 2017; Tempa et al. 2024: Baltyzhakova and Romanchikov 2021).

Summarizing the scientific review, a system of assessment of urban green infrastructure is proposed. It is based on the global concept of sustainable development (Gagarina 2023; Pashkevich and Danilov 2023) (Fig. 1). It is obvious that legal justice, which involves assessment of urban green infrastructure based on its (legal) illegal use, as well as social provision, environmental stability, and economic efficiency, should become a mandatory element of the sustainable development concept of urban areas. In this regard, the goal of this study was formulated: to develop a methodology for assessing urban green infrastructure in order to identify green areas that are not being used for their legal purpose.

MATERIALS AND METHODS

St. Petersburg green fund

St. Petersburg is a million-plus city of federal significance, the second most populous city in Russia, and the largest cultural, economic, scientific, and transport center. It is located (Fig. 2) in the north-west of the Russian Federation (59º57′ N, 30º19′ E), its area is more than 1.4 thousand km2; the population is 5.5 million people. St. Petersburg's administrative-territorial division is made up of 18 administrative districts.

The city's green fund includes a system of green areas that perform various functions:

1. Public green space territories are green areas used for recreational purposes by an unlimited number of people. They are divided into three categories: citywide significance, local significance, and landscaping reserve. The main difference between these groups is which department they belong to: activities of the first and third

[2] Borisova V. and Bondarev D. (2024) Development of the Krylatskie Hills Park in the Krylatskoye District: Residents came to a meeting with State Duma Deputy Dmitry Kuznetsov over the improvement of the Krylatskie Hills. Available at: https://msk1.ru/text/gorod/2024/08/20/73983644/?ysclid=m02rr75b5398485376.

[3] An attempt to build in the Gladyshevsky nature reserve resulted in a criminal case. (2017). Available at: https://www.fontanka.ru/2017/03/13/102/?ysclid=m02sfg84vh566552018.

[4] Khruleva I. (2023) An illegal cottage village was found in the reserve «Baidarsky». Available at: https://sevastopol.press/2023/11/30/v-zakaznike-bajdarskij-nashli-nezakonnyj-kottedzhnyj-poselok/?ysclid=m02t34vplh184460060.

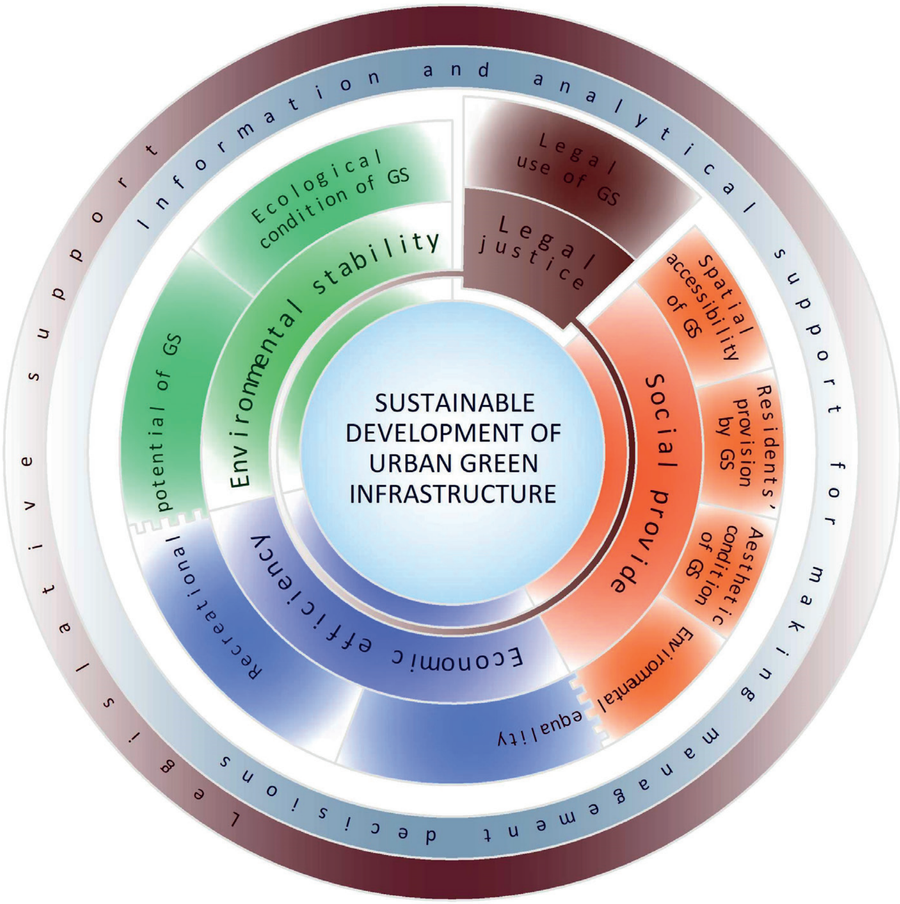


Fig. 1. System of urban green infrastructure assessment as part of the sustainable development concept of urban areas (compiled by the author): GS – green spaces

Fig. 2. Location of Saint Petersburg (compiled by the author)

categories are provided by the St. Petersburg authorized executive body of state power; green territories with local significance are managed by the local authorities of intra-city municipalities of the city; landscaping reserves are undeveloped areas potentially intended for landscaping.

2. Special-purpose green areas are intended for landscaping areas with special use conditions and perform the function of protective landscaping.

3. Green territories with limited use - these land plots are owned by St. Petersburg, and access to green spaces on them may be restricted by the copyright holder.

4. Protected forest areas include urban forests and forest park areas within the city boundaries.

5. Specially protected natural areas (SPNA) within the borders of St. Petersburg.

The author's research is devoted to the analysis and assessment of the first group of territories, which are further designated as territory of PGS or PGS.

As of 01/05/2024, the St. Petersburg PGS has an area of 8,383.4 ha, including citywide significance PGS - 6,078.0 ha, local significance PGS - 1,843.4 ha, landscaping reserve PGS - 462.0 ha (St.-Petersburg Law dated 10/08/2007 No. 430-85 "On public green spaces"). The distribution of PGS by the city administrative districts is presented in Fig. 3, 4.

PGS are represented by parks, gardens, squares, boulevards, alleys and forest parks (Table 1).

In the PGS system, public gardens predominate in number, and their area often does not exceed 1 ha. This indicates the fragmentation of the city's green fund - a negative anthropogenic process associated with the

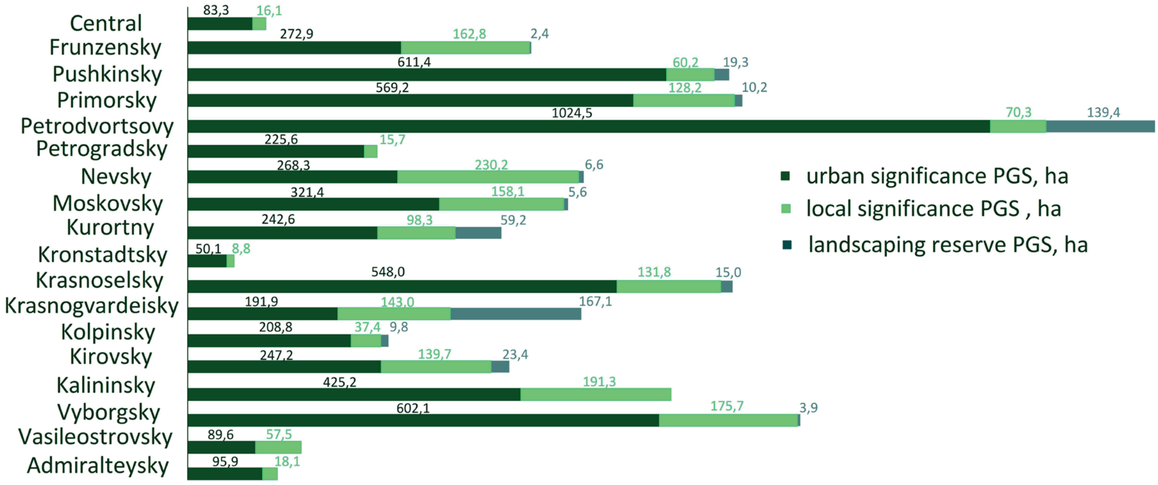


Fig. 3. PGS area of St. Petersburg administrative districts (ha) as of 02/01/2024 (compiled by the author)

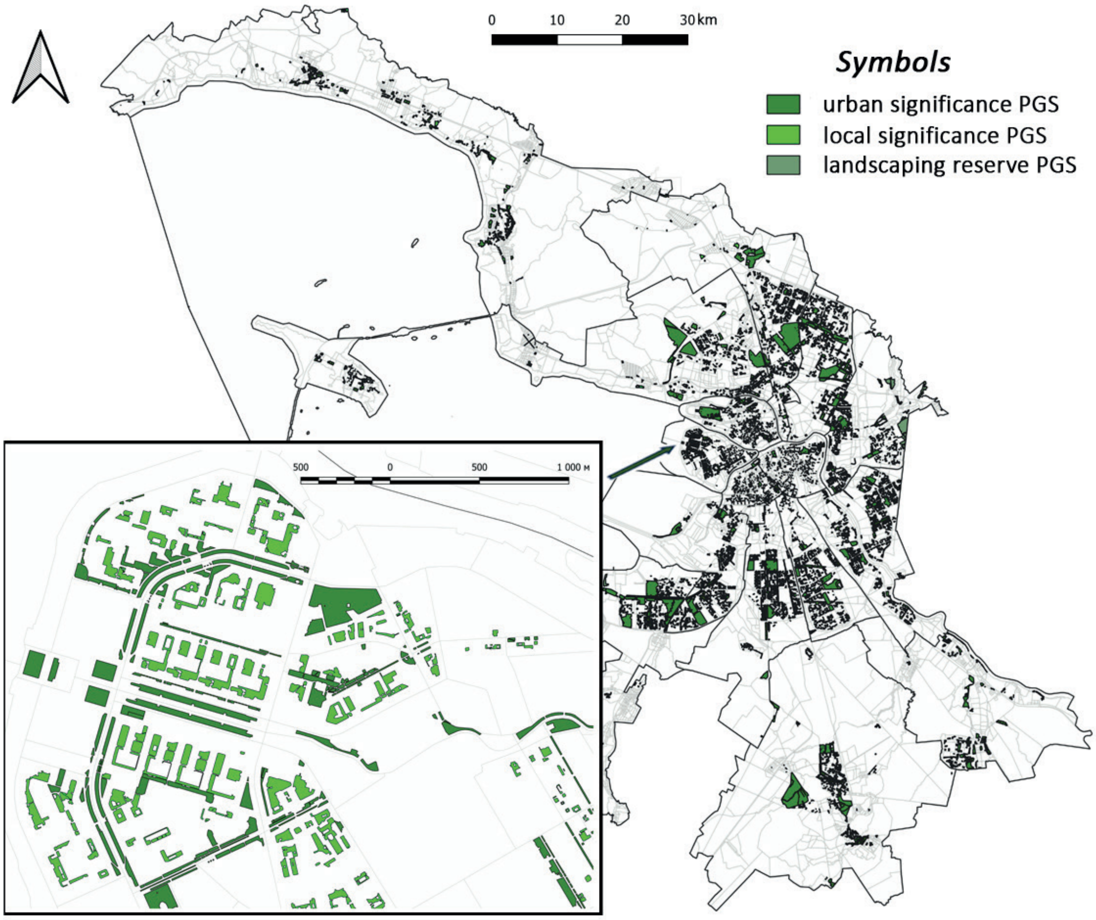


Fig. 4. PGS system of St. Petersburg: citywide significance, local significance, and landscaping reserve (compiled by the author)

Table 1. Distribution of St. Petersburg PGS by landscaping objects (compiled by the author)

PGS category	Parks	Gardens	Squares	Boulevards	Alleys	Forest parks	SUM
	in the numerator – area, ha; in the denominator – quantity, units						
citywide significance	3671.7 / 95	485.1 / 138	1400.7 / 1688	344.8 / 134	1.9 / 1	173.8 / 1	6078.0 / 2057
local significance	6.6 / 2	0.5 / 1	1824.3 / 5604	10.0 / 11	2.0 / 2	0 / 0	1843.4 / 5620
landscaping reserve	124.3 / 7	0 / 0	243.6 / 79	3.5 / 3	0 / 0	90.5 / 1	462.0 / 90
TOTAL	3802.6 / 104	485.6 / 139	3468.5 / 7371	358.3 / 148	3.9 / 3	264.3 / 2	8383.4 / 7767

destruction of continuous habitat. Reducing the average area of green areas increases their permeability and sensitivity to degradation and also increases environmental pressure on these spaces (Nasehi and Namin 2020; Nazombe and Nambazo 2023).

Creation of a geospatial database of St. Petersburg PGS using QGIS

The creation of a geospatial database, as the best way to systematize and visualize semantic and spatial data (Kolesnik et al. 2022), was carried out in the free cross-platform geographic information system Quantum GIS 3.34.0. The project coordinate system was adopted as WGS 84.

For the purposes of the study, a Sentinel-2 multispectral image (the European Space Agency (ESA)) was used. Image resolution is 10 m, and image coverage is the territory of St. Petersburg as of June 15, 2023 (image ID: S2B_MSIL2A_20230615T092559_N0509_R136_T35VPG_20230615T120159). Cloud cover was less than 3%. Such images are widely used to assess vegetation by researchers around the world (Wu et al. 2023; Giuliani et al. 2021). The image was processed at level 2A; accordingly, radiometric, geometric, and atmospheric corrections were performed for it. The summer survey season is justified by the active growing season of plants, which is necessary to determine the normalized difference vegetation index (NDVI). The earliest reference to the use of NDVI is given in the study by Rouse et al. (Rouse et al. 1974).

At the first stage, two raster layers B04 and B08 were loaded into the GIS project, corresponding to the red (Red) and infrared (NIR) spectral channels.

The QGIS raster calculator (Toolbar - Data Analysis - Raster Analysis - Raster Calculator) allowed us to calculate the NDVI (Eq.(1)), which is based on the unique spectral response of anthropogenic objects, vegetation, and water bodies (Kumar et al. 2023; Jin et al. 2024):

$$NDVI = \left(\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \right) \quad (1)$$

where:
ρ_{NIR}– reflection in the near-infrared region of the spectrum (spectral channel B08); ρ_{RED}– reflection in the red (visible) region of the spectrum (spectral channel B04).

The second stage involved using QGIS to download data from the Regional Geographic Information System of St. Petersburg[5]. A new connection to the RGIS server was created by adding the WFS layer, which made it possible to add to the GIS project a layer of PGS boundaries in St. Petersburg, as well as layers of cadastral districts and blocks in vector form. The attribute information of the PGS layer encompasses the administrative district where the PGS is situated, its legal PGS number, its name and location, its area, and the number of the scheme that approved the PGS boundaries. The listed data is publicly available, and if it is not possible to use the RGIS St. Petersburg server, you can use the cartographic application of the St. Petersburg Law “On Green Spaces for Public Use” and manual digitization methods.

In the third stage, a grid of 10×10 m squares was created over the entire city territory using a separate vector layer (“pixel-by-pixel” grid). In the process of spatial analysis and assessment of territories, a similar approach is common (Raguzin et al. 2023; Kovyazin et al. 2021: Kopylova et al. 2023). The grid square was the same size as the pixels in the multispectral image channels that had already been loaded, and the edges of the grid square lined up with the edges of the pixels in the red and NIR raster images. Subsequently, such an overlay of vector and raster layers made it possible to perform a “pixel-by-pixel” analysis, transferring the data obtained from a raster multispectral image to the vector square of the grid.

To reduce the vector mesh layer’s data volume (the file size was initially more than 25 GB), it was trimmed to the PGS layer. The QGIS Zonal Statistics tool allowed us to create an additional vector layer that included NDVI values for each grid square within the PGS boundaries only.

Classification of objects within the PGS territory

In addition to vegetation (trees, shrubs, flower beds, lawns), buildings, structures, artificial surfaces for various purposes, as well as water bodies, can be located on the PGS territory (Bolkaner and Asilsoy 2023).

For forests, the issue of classifying forest vegetation according to the NDVI values has been widely studied (Tempa et al. 2024; Kovyazin et al. 2023). In particular, in the absence of forest vegetation, NDVI values are in the range of 0-0.2, for low vegetation - 0.2-0.4, for high vegetation - 0.4-0.6, for closed and very dense vegetation the values NDVI are 0.6-1.0 (Kovyazin et al. 2021). The index values are also known for various types of tree and shrub vegetation. For example, a deciduous forest is characterized by an average NDVI value of 0.83, and shrubby vegetation – 0.68 (Priya et al. 2023).

For urban conditions, the NDVI values of green spaces may differ due to the aggressive anthropogenic load on the natural environment. Also, green areas of cities are not always represented by a closed tree stand. Rather, on the contrary, in gardens, squares, and boulevards, a sparse tree

[5] *https://rgis.spb.ru/*

stand predominates with the presence of parterres, garden and meadow lawns, shrubs, artificial objects, and surfaces.

To test this hypothesis, a comparison method ("pixel-by-pixel" analysis) was used. A Yandex Satellite base layer was added to the GIS project using the QuickMapServices plugin. This layer was superimposed on a grid of squares within the PGS boundaries, created at stage 2.2. The NDVI values of the "single-digit" squares were visually compared with the RGB image of the same area of the Yandex Satellite image. "Single-digit" squares were defined as those squares that contained only one type of vegetation, cover, or object within their boundaries. The set of analyzed squares met the condition of representativeness.

Classification of vegetation, coverings or objects located in the PGS territory, using NDVI value, was performed using the "Boxplot" method in the Python programming environment. The program code is available[6].

Identification of PGS areas that potentially conflict with their standard functions

Based on the NDVI interval corresponding to areas without vegetation (step 2.3), we identified squares of the "pixel-by-pixel" grid that could potentially be used for incorrect purposes (in the QGIS project they were highlighted in red, which made it possible to visualize the result). A SQL query was used to trim the data.

Subsequent analysis of "suspicious" squares was carried out using a visual comparison of the corresponding Yandex Satellite area with legal types of economic activity within the PGS territory. Field surveys were also done, which made it possible to clarify the results of remote sensing methods.

Technology of assessing urban green infrastructure to identify misuse green areas

Fig. 5 presents a schematic representation of the technology for assessing urban green infrastructure to identify misused green areas.

RESULTS

Calculation of the NDVI

After loading two raster layers (B04 and B08) of a multispectral image of St. Petersburg territory into the GIS project, using the QGIS "Raster Calculator" function a raster image (separate layer) was obtained containing NDVI values for each pixel of the study area. The vegetation index calculation's graphical result was displayed in panchromatic color. To obtain a color image, in the properties of the raster layer, the image rendering was changed to "Single-channel pseudo-color" and a color map (palette) was added (Fig. 6). The palette can be created manually or loaded from an already created .txt file. The resulting images and palette file are available[7].

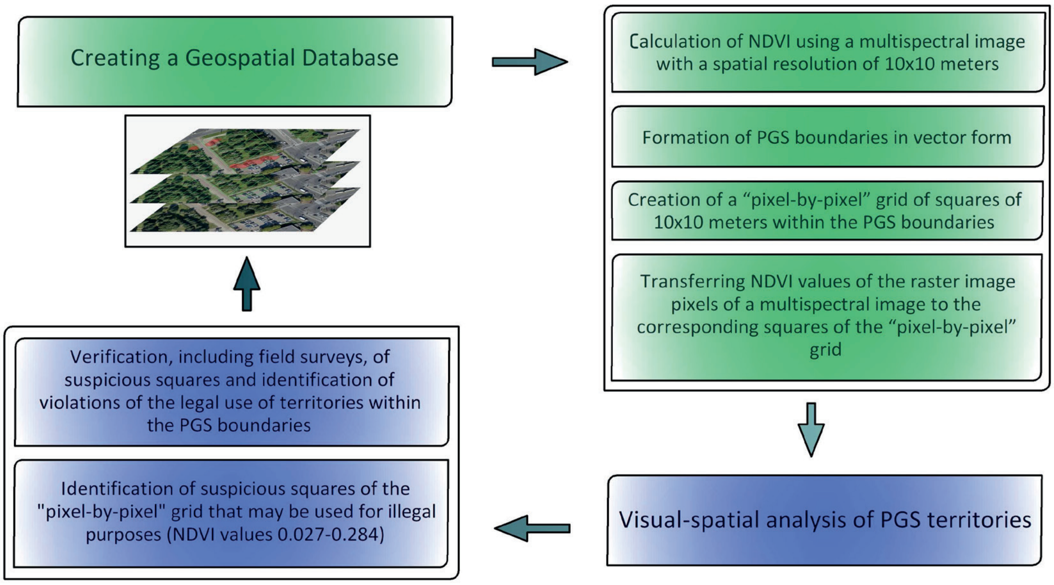


Fig. 5. Technology of assessing urban green infrastructure to identify misused green areas (compiled by the author)

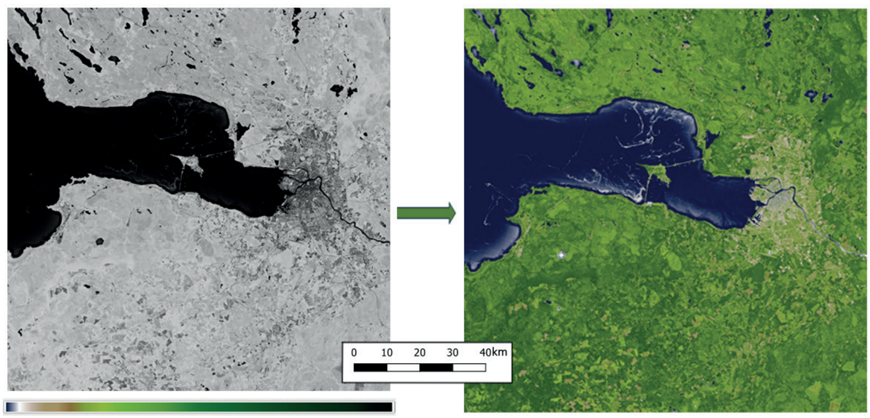


Fig. 6. Calculation and visualization of NDVI as of June 15, 2023 (compiled by the author)

[6] *https://drive.google.com/drive/folders/1RUKMATPKbchYFyWESVPNkZyzBhndu93X?hl=ru*
[7] *https://drive.google.com/drive/folders/1KkXxfYQoEVkS4p_8iHSq-uq_AENFcfb3?hl=ru*

Uploading RGIS data

The result of downloading data from the RGIS of St. Petersburg was five vector layers: citywide significance PGS; local significance PGS; landscaping reserve PGS; boundaries of cadastral areas; boundaries of cadastral blocks. The boundaries of cadastral districts and blocks correspond to the cadastral division of the Russian Federation territory.

Creating a grid of squares ("pixel-by-pixel" grid) and determining NDVI values for squares within the PGS boundaries

A grid of 10×10 m squares was created using a separate vector layer (Vector – Analysis – Create Grid). Next, it was trimmed along the boundaries of the layer containing the St. Petersburg PGS (Vector – Geoprocessing – Crop). Using zonal statistics (Analysis Tools - Raster Analysis - Zonal Statistics), an NDVI value was calculated at stage 3.1, for each square within the PGS boundaries (Fig. 7).

Comparison of NDVI values and Yandex Satellite images within the boundaries of the PGS square ("pixel-by-pixel" analysis)

The obtained NDVI values of PGS squares within the borders of St. Petersburg range from -0.0809 to 0.7166. For further "pixel-by-pixel" analysis citywide significance PGS located in different areas of the city were selected (Fig. 8). The condition of mandatory analysis of squares with minimum and maximum NDVI values was also taken into account.

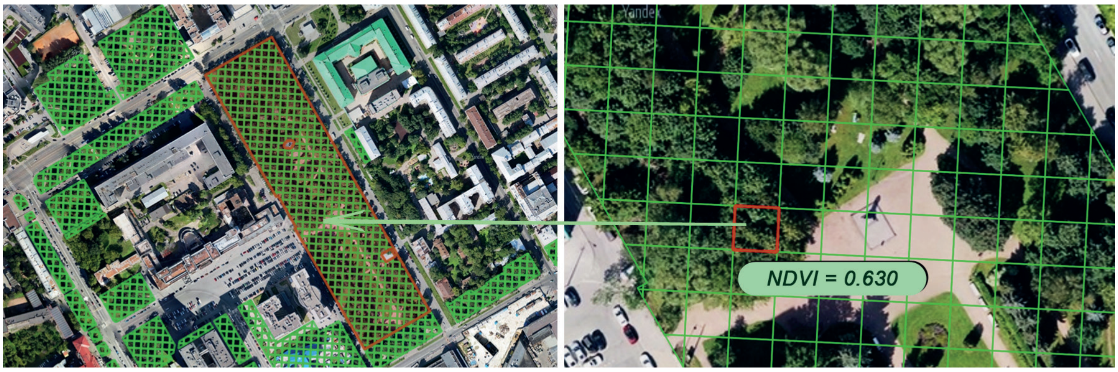


Fig. 7. Garden «Vasileostrovets» - citywide significance PGS No. 2005 (compiled by the author)

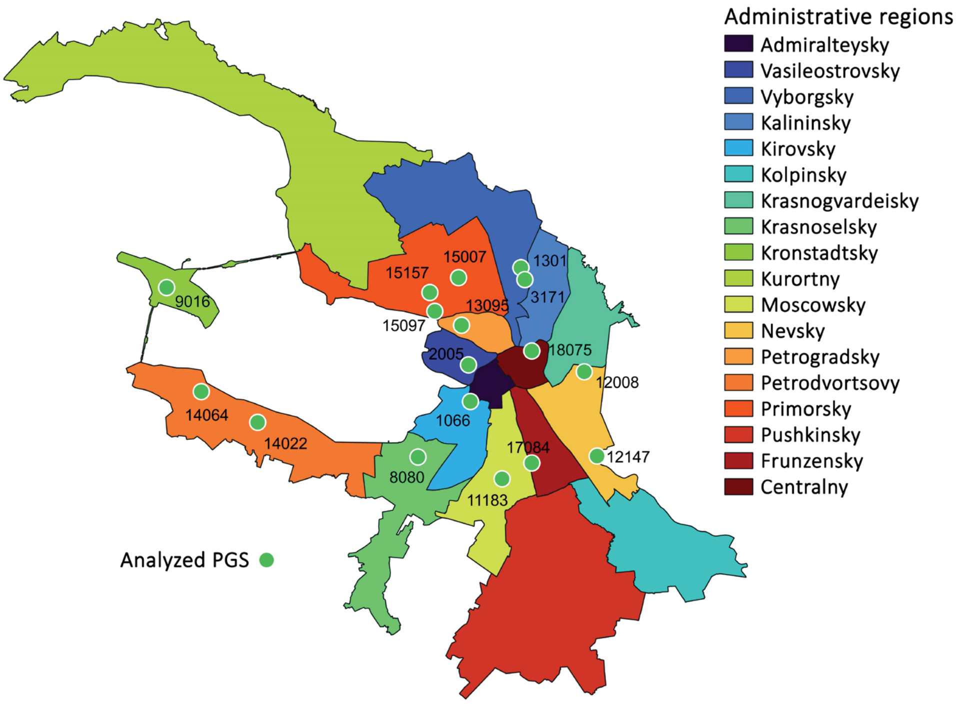


Fig. 8. Location of the PGS for comparing NDVI values and the Yandex Satellite image within the boundaries of the PGS squares. Map key: No 1066 – Ekateringof Park on Ekateringof Island; No 11183 - square w/num., Pulkovskoye Highway near house 15, bldg. 2; 12008 - Yablonovsky garden between the Okkervil Riv., Voroshilov Str. and Latvian Riflemen Str.; No 12147 - Spartak Garden between Obukhovskaya Oborony Ave., Rybatsky Ave. and the Neva Riv.; No 13095 - Primorsky Victory Park between Grebny Canal, Ryukhin St. and the Malaya Nevka R.; No 14022 - English Park between St. Petersburg Ave., Red Cadets Blvd. and Blan-Menilskaya Str.; No 14064 – square w/num. between Dvortsov Prospect and Aleksandrovskaya Str.; No 15007 – boulevard w/num. on Dolgoozernaya Str. from Planernaya Str. to Korolev Ave.; No 15097 - Park named after the 300th anniversary of St. Petersburg between the Gulf of Finland and Primorsky Prospect; No 15157 – square w/num. on Shuvalovsky Prospect from Furniture Str. to Bogatyrsky Ave.; No 17087 - Rescuers Square northeast of the intersection of Bukharestskaya Str. and Fuchik Str.; No 18075 - Tavrichesky Garden between Kirochnaya Str., Tavricheskaya Str., Shpalernaya Str. and Potemkinskaya Str.; No 2005 - Vasileostrovets garden between Sredny Ave. V.I., 25th Line V.I., Bolshoy Ave. V.I. and Club Lane.; No 3001 - Sosnovka Park between Northern Ave., Tikhoretsky Ave., Svetlanovsky Ave., Torez Ave. and Vitkovsky Str.; No 3171 – park w/num. near Olginsky pond; No 8080 - South Primorsky Park on Peterhofskoye Highway, bounded by the Valor Str. And Marshal Zakharov Str.; No 9016 – square w/num. at the intersection of Citadel highway and Hydrobuilders Str. (compiled by the author).

In total, more than 7.5 thousand "single-digit" squares were analyzed (Fig. 9), within the boundaries of which NDVI values and a visual image of the corresponding section of the PGS according to Yandex Satellite were compared.

The classification of vegetation, surfaces, and other objects in the PGS was carried out using the boxplot method, which made it possible to determine the NDVI ranges for three types of vegetation, buildings, artificial road surfaces, sports grounds, beaches, and water surfaces, as well as to cut off outliers (Fig. 10).

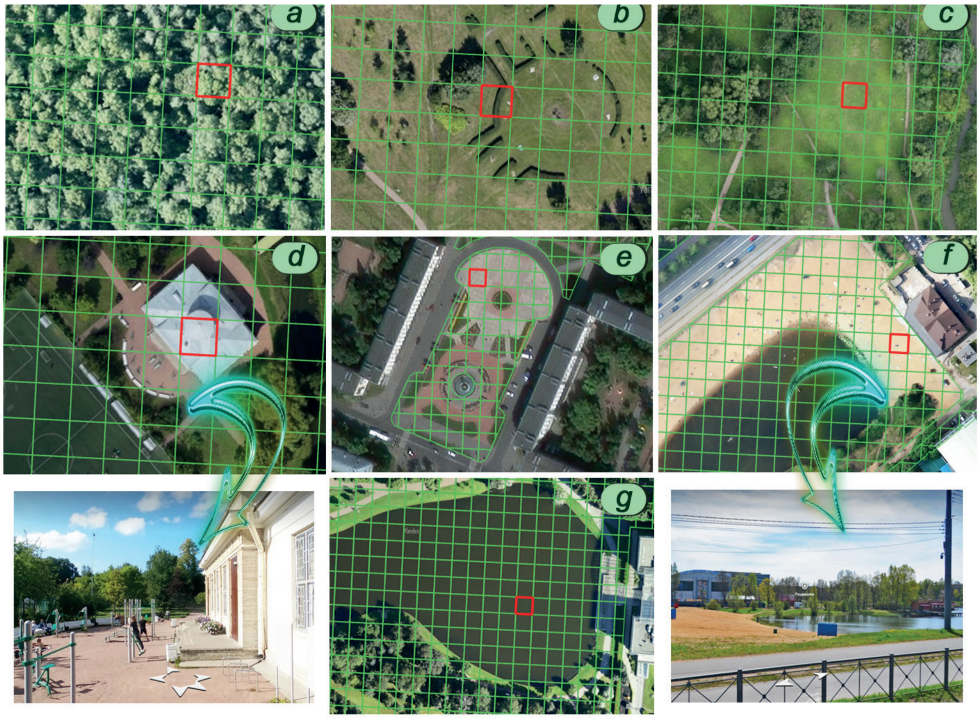
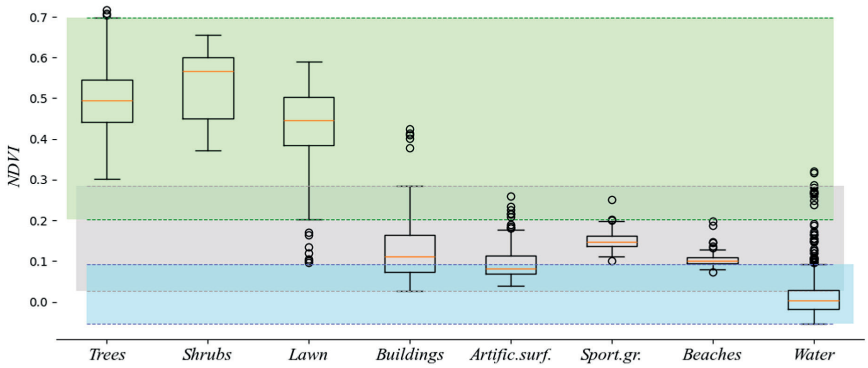


Fig. 9. Types of vegetation, coverings and other objects in the territory of the PGS. Map key: (a) Trees; NDVI = 0.513; No 3001 - Sosnovka Park between Northern Ave., Tikhoretsky Ave., Svetlanovsky Ave., Torez Ave. and Vitkovsky Str.; (b) Shrub vegetation; NDVI = 0.445; No 17087 - Rescuers Square northeast of the intersection of Bukharestskaya Str. and Fuchik Str.; (c) Herbaceous vegetation (lawn); NDVI = 0.524; No 12147 - Spartak Garden between Obukhovskaya Oborony Ave., Rybatsky Ave. and the Neva Riv.; (d) Buildings; NDVI=0.053; No 18075 - Tavrichesky Garden between Kirochnaya Str., Tavricheskaya Str., Shpalernaya Str. and Potemkinskaya Str.; (e) Artificial surfaces; NDVI=0.038; No 14064 – square w/num. between Dvortsov Prospect and Aleksandrovskaya Str.; (f) Beaches; NDVI = 0.083; No 3171 – park w/num. near Olginsky pond; (g) Water (incl. blooming water and water with algae); NDVI = 0.004; No 13095 - Primorsky Victory Park between Grebny Canal, Ryukhin St. and the Malaya Nevka R. (compiled by the author, including using Yandex Maps images).



Boxplot parameters	Trees	Shrubs	Lawn	Buildings	Artific.surf.	Sport.gr.	Beaches	Water
Quantity	6402	78	224	93	158	102	78	372
Average	0,497	0,534	0,433	0,131	0,097	0,151	0,105	0,021
Max value	0,717	0,656	0,591	0,425	0,259	0,251	0,198	0,322
Min value	0,302	0,373	0,097	0,027	0,038	0,100	0,074	-0,053
Upper mustache	0,698	0,656	0,591	0,284	0,177	0,200	0,129	0,092
Lower mustache	0,302	0,373	0,203	0,027	0,038	0,100	0,078	-0,053

Fig. 10. Boxplot method for classifying vegetation, coverings and other objects on the territory of the PGS (compiled by the author)

As a result, three consolidated categories of objects located within the territories of the PGS were identified (Table 2).

The research by Klimanova (2021), which determines NDVI intervals for a surface without vegetation (0.18-0.30) and a surface with vegetation (more than 0.30), demonstrates the comparability of the results in Table 3.

During the "pixel-by-pixel" analysis, several patterns were also identified:

1. NDVI of water bodies decreases with increasing depth;

2. on the shallows, the vegetation index takes on a positive near-zero value;

3. for blooming water or water with a lot of algae, NDVI reaches values of 0.3. It is obvious that the index responds to an increase in chlorophyll in aquatic vegetation. The boxplot method allows you to cut off such inflated values, highlighting them as outliers.

Identification of violations within the boundaries of the St. Petersburg PGS

According to the St. Petersburg legal zoning, PGS are located in various territorial zones: recreational (TR0-2, TR2, TR3-2, TR4, TR5-2), residential (T1ZH2-2, T2ZH1, T3ZH1, T3ZH2, T3ZhD3), public-business (TD1-1_1, TD1-1_2, TD2_1, TD1-2_2), multifunctional (T3ZhD3), external transport facilities (TI4_1), road network (TU), agricultural use (TR2/TS1). For PGS with citywide importance, the most common zones are TP2 (preservation and arrangement of open green spaces during their active use) and TP4 (preservation and arrangement of recreational territories of palace and park complexes and other historically valuable city-forming objects and spaces), for PGSwith local significance, different types of residential areas.

Also, according to the Law of St. Petersburg "On Administrative Offenses in St. Petersburg", the placement of vehicles in PGS, green spaces performing special functions, restricted green spaces, lawns is prohibited and entails administrative liability.

Taking into account the consolidated categories of objects located within the territories of the PGS (Table 2), an SQL query was executed. Its result was the "gray" zones within the PGS territories, where the vegetation index NDVI lies in the range of 0.027-0.284, which corresponds to artificial objects (Fig. 11).

The resulting "gray" zones are represented by different categories of objects and surfaces:

1. areas without vegetation (trampled or with artificial coverings);

2. areas occupied by parking, cluttered areas;

3. areas occupied by temporary facilities (underground metro facilities under construction that require temporary operation of green areas (Volokhov and Mukminova 2021));

4. water bodies;

5. areas occupied by structures and objects that do not conflict with the recreational function of the PGS.

Of the entire set of citywide significance PGS, the identified PGS with the presence of "gray" zones account for more than 50% (more than 1000 PGS). And at this stage, the task arises of differentiating "gray" zones according to compliance (not compliance) with the functions of PGS.

Identifying "gray" areas, which include cluttered areas or areas occupied by unauthorized parking or buildings, can be done in several ways:

• non-automated analysis of PGS by comparing the location of "gray" zones with Yandex Satellite (or other image of the territory with sufficient resolution), as well as with field survey data, if necessary;

• application of neural networks, including convolutional (Shestakov et al. 2023) for automatic classification.

In this study, the first method was used. The implementation of the second method is a promising direction for future research.

During the analysis, citywide significance PGS were identified, economic activities on the territory of which

Table 2. NDVI intervals for consolidated categories of objects located within the territories of the PGS (compiled by the author)

Consolidated categories	Minimum NDVI value	Maximum NDVI value
Landscaping	0.203	0.698
Artificial objects	0.027	0.284
Water	-0.053	0.092

Fig. 11. SQL query result: red squares have NDVI values in the range 0.027-0.284 (compiled by the author)

completely or partially do not comply with urban planning regulations and regional legislation (Fig. 12, 13). Within the boundaries of the identified PGS, there are buildings with an obvious non-recreational function, such as spontaneous parking, litter, sand dumps, and so on.

The list of PGS with identified inconsistencies with their intended purpose, including photographic documentation, is available[8].

Thus, the problems identified during the "pixel-by-pixel" comparative analysis boil down to the following aspects:

- unauthorized placement within the PGS boundaries of objects of production, storage, trade, transport or other non-recreational purposes, implementation of related economic activities that do not comply with urban planning regulations;
- spontaneous parking prohibited by regional legislation;
- discrepancy between the purpose of PGS and legal zoning, which provokes a contradiction between the Law of St. Petersburg "On Rules of Land Use and Development of St. Petersburg" and the Law of St. Petersburg "On Administrative Offenses in St. Petersburg".

DISCUSSION

The total official area of St. Petersburg PGS is 8383.4 ha, and the permanent population of St. Petersburg is more than 5.5 million people (as of 01/01/2024). Taking these indicators into account, the average PGS provision of city residents is about 15 m^2/person, while the established norm is 10 m^2/person. (Urban Development. Urban and Rural Planning and Development. Code of Practice 42.13330.2016; Ministry of Construction and Housing and Communal Services of the Russian Federation: Moscow, Russia, 2016. (In Russian)). PGS occupy 6% of the city's total area.

In 2024, the area of citywide significance PGS of St. Petersburg increased by more than 75 ha (1.2%) due to the assignment of PGS status to a number of green areas, as well as the clarification of their boundaries. Obviously, this method of increasing greenery is of a formal nature and does not actually increase the number and area of green spaces. PGS status should be a mechanism for protecting green areas from illegal use, but in practice this mechanism does not work satisfactorily.

In addition to PGS status, green areas must have clearly defined boundaries, information about which must be entered into the Real Estate Cadastre in accordance with the state cadastral registration procedure. Currently, only a small part of PGS is registered. At the same time, during the author's research, discrepancies in the area of individual PGS according to the real estate cadastre data and according to the RGIS data (according to the Law of St. Petersburg dated October 8, 2007 No. 430-85 "On public

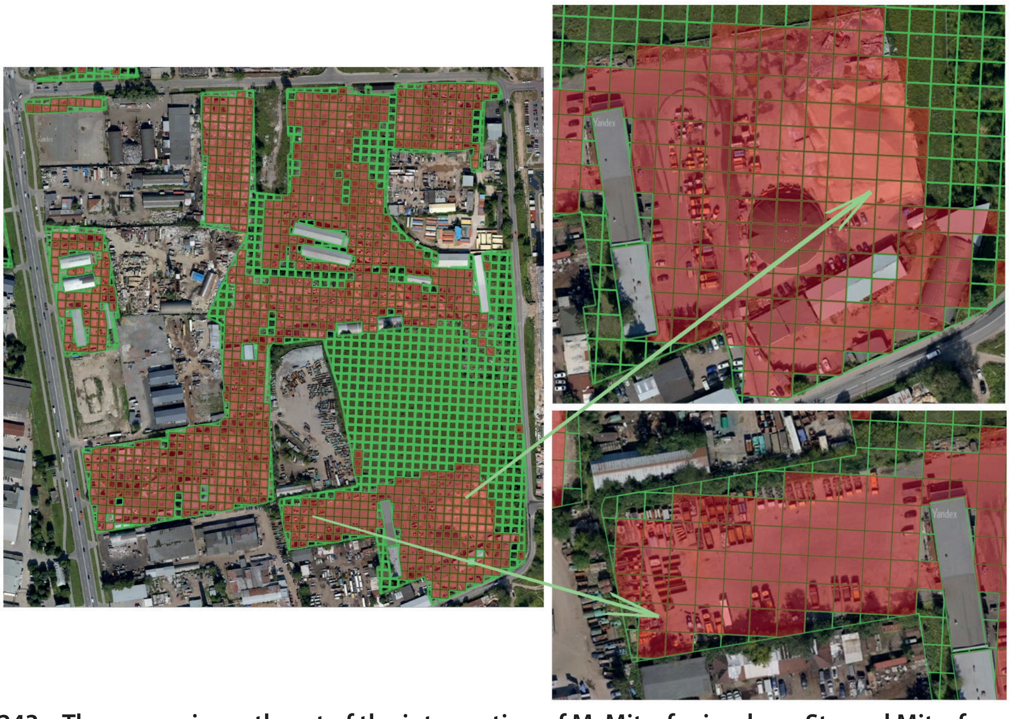


Fig. 12. No. 11243 – The square is northeast of the intersection of M. Mitrofanievskaya Str. and Mitrofanyevskoe Highway (compiled by the author)

Fig. 13. No. 15097 – Park named after the 300th anniversary of St. Petersburg between the Gulf of Finland and Primorsky Prospect (compiled by the author)

[8] *https://docs.google.com/spreadsheets/d/1JGcYRlafaNKDQIbEtu3WdJ_zT2QrSwrldHDjgg5qxOk/edit#gid=0*

green spaces use") were identified. For specific examples, we can cite citywide significance PGS No. 1028 (a public garden at the intersection of 7th Krasnoarmeyskaya Str. and Egorov Str.) and No. 5090 (Leningradsky Square on Stachek Avenue at 114a; Fig. 14). Such inconsistencies indicate unregulated interdepartmental interaction between the Rights Registration Authority (Rosreestr) and the Property Relations Committee of St. Petersburg.

The solution to these problems should be a concept adopted at the state level that defines the principles, methodological foundations, and methods of accounting, assessment, and monitoring of urban green infrastructure (Slovic et al. 2023), and its result will be a mechanism of information and analytical support for making management decisions.

The authors Klimanova et al. rightly note that forms of green areas transformation can be changes when woody or non-woody vegetation is replaced by built-up or other "non-green" areas (Klimanova et al. 2021). To quickly respond to such actions with minimal labor and financial costs, remote methods are optimal. Many researchers use multispectral Landsat imagery with a spatial resolution of 30×30 m. But such spatial resolution provokes inaccurate results (Klimanova et al. 2021). This work uses Sentinel-2 images with a spatial resolution of 10×10 m, which increases the reliability of the results. It is also worth noting that an alternative to high-resolution satellite images can be the results of shooting from unmanned aerial vehicles, which allow increasing the resolution to tens of centimeters. However, in relation to the largest city territories, this option requires additional financial investments, time, and labor resources.

Moving on to the discussion of the misuse problem of territories within the PGS boundaries, it is worth noting that violations are associated with several reasons:

• firstly, the lack of landscaping, including fencing or side stones along the PGS border, provokes collisions of vehicles with "green" areas (No. 17157);

• secondly, the implementation of necessary temporary construction work, in connection with the creation of socially significant infrastructure, reduces the total area of the PGS for the construction period, which can last more than one year (No. 2015, No. 2019);

• thirdly, the initially incorrect establishment of the PGS boundaries leads to the erroneous inclusion of residential buildings and adjacent courtyard areas (No. 13174), non-residential objects (No. 5150), as well as organized parking spaces in landscaping areas (No. 17010, No. 5090, No. 5211);

• fourthly, the lack of an effective and operational mechanism of monitoring the PGS legal use and the lack of systematic environmental education lead to systematic violations in the form of unauthorized parking (ZNOP No. 15062, No. 3134, No. 4179).

These reasons result in an actual decrease in the area of greenery, which is confirmed by the authors (Klimanova et al. 2021), noting the "loss of green infrastructure" in Russian cities of about 6%. At the same time, formal indicators of green space "on paper" are overestimated, and, accordingly, when the indicator of the population's provision of green space is calculated, the official results cannot be considered reliable. According to the author's calculations, for citywide significance PGS, the area of green areas with misuse was more than 20 ha (0.3% of the area of citywide significance PGS in St. Petersburg according to official statistics (Fig. 2)). Accordingly, there will be a similar decrease in the population's PGS provision for the city in general. Differentiation by city administrative districts may differ from the citywide result.

The study has some limitations, among which the following can be highlighted: the original cartographic material; technical means of data processing; restrictions related to seasonality of observations.

When using multispectral satellite images, resolution plays an important role. The author's study used publicly available Sentinel-2 images with a resolution of 10 m. Even higher resolution images (for example, from unmanned aerial vehicles) will improve the accuracy of the assessment results of green areas. But, in this case, the cost of such cartographic material for the entire city, taking into account the time dynamics, will be disproportionately high. Potential consumers of the proposed technology may not have the opportunity to purchase ultra-high-resolution images due to budgetary constraints. In our opinion, poor funding of urban landscaping is a deep problem of sustainable urban development, and to improve the life quality of citizens, it is necessary to increase investment in this area (Aram 2024).

Additionally, the spatial resolution of images directly determines the pixel size. As a result, the vegetation index's calculated value is assigned to a 10×10 m area. If the PGS area is less than 100 m^2, or the area is linear and less than 10 m wide, the NDVI is erroneously influenced by the objects and coverings surrounding the green area, thereby underestimating its value. Increased demands are placed on computer hardware because data spatial analysis of a vast metropolitan area requires increased RAM, a sufficiently powerful video card, as well as a capacious HDD for storing images, the size of which is usually about 1 GB. To determine vegetation indices, satellite images taken exclusively during the growing season of active plant growth are used (and season depends on the climatic characteristics of the region).

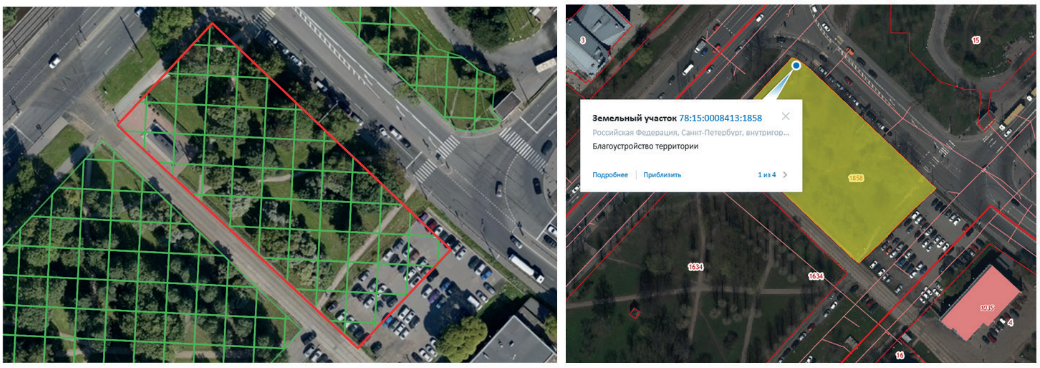


Fig. 14. Leningradsky Square on Stachek Ave. at 114a. Map key: on the left - the PGS boundaries according to the RGIS of St. Petersburg (area 3.9310 ha); on the right - the PGS boundaries according to the Real Estate Cadastre (3.7945 ha) (compiled by the author, including according to data[9])

[9] *https://pkk.rosreestr.ru/*

CONCLUSIONS

The study is scientifically unique because it confirms the ranges of NDVI values for different types of vegetation, coverings, and objects in the PGS. The NDVI values in the city and in the forest have a different upper threshold. For metropolitan conditions, the maximum value is 0.7, while forest plantations can have an index of up to 1.0. The poor ecology of urbanized areas and the sparseness of urban vegetation primarily explain this. Also, the concept of sustainable development of urban green infrastructure based on its assessment system has scientific significance.

The following results have practical significance: (1) technology of urban green infrastructure assessment to identify public green spaces with misuse; (2) geospatial database PGS of St. Petersburg, which includes vector layers: citywide significance PGS; local significance PGS; landscaping reserve PGS; "pixel-by-pixel" grid of squares, as well as layers with calculated NDVI values, including values indicating misuse of public green areas; (3) identified PGS areas with obvious violations of the use of green areas. ■

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