RESEARCH PAPER

# URBAN GREEN INFRASTRUCTURE OF RUSSIAN SOUTH: SPATIAL JUSTICE - ECOLOGICAL EFFICIENCY NEXUS

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ABSTRACT. The incorporation of nature-based solutions into urban planning and development policies has become a pressing issue in many large cities worldwide, aiming to improve the urban environment and the well-being of city-dwellers. However, the establishment and management of urban green infrastructure can be expensive and may lead to spatial injustice or be ecologically inefficient due to the planning decisions. This study focuses on the Spatial Justice-Ecological Efficiency Nexus of urban green infrastructure in large Caucasian cities of Russia, where urbanization rates are rapidly increasing. The hypothesis of this study is that green infrastructure in Russian cities predominantly has an ecological aspect, meaning that it provides a large volume of ecosystem services that are still unavailable to a significant portion of the urban population. To explore this topic, we aim to assess the balance between the social and ecological aspects of green infrastructure in six case study cities, including Makhachkala, Grozny, Nalchik, Maykop, Vladikavkaz, and Stavropol. The assessment framework includes 12 indicators, divided into two categories: spatial justice (6 indicators) and ecological efficiency (6 indicators). The spatial justice indicators assess the availability, accessibility, and distribution of green infrastructure, while the ecological efficiency indicators evaluate the performance of regulating and supporting ecosystem services. The results revealed that despite the common prevalence of ecological side in large Russian cities, the spatial justice side in the southern cities generally dominates over the ecological side, with most cities having an unbalanced nexus. Green infrastructure in the studied cities has a low ecological input, with a mean total score of around 300 points (out of 600), with most cities lacking protected areas and green areas beyond the edge effect. Meanwhile, the social side of the nexus is more developed, with an average score of 400. The study highlights the need for a more integrated approach to urban green infrastructure planning, considering both justice and ecological aspects to ensure a more just and sustainable urban environment. Overall, in this research we introduce a multidimensional approach to understanding the functions and qualities of green infrastructure that will allow for a more comprehensive assessment and planning of the rapidly growing southern cities. This study contributes to the understanding of the complex relationships between urban green infrastructure spatial justice and ecological efficiency, providing valuable insights for urban planners, policymakers, and stakeholders seeking to create more sustainable and equitable urban environment.

KEYWORDS: urban green infrastructure, social-ecological functions, green justice, ecological efficiency, spatial distribution, North Caucasian cities

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## INTRODUCTION

Today, many large cities around the world are striving to incorporate nature-based solutions into their planning and development policies in order to improve the urban environment and, as a result, the well-being of the urban population. Being the major source of ecosystem services and the core nature-based solutions in the city, green infrastructure aims to mitigate negative impacts of urban grey infrastructure, including different types of pollution, heat island effect, erosion, and psychological discomfort, and to provide a suitable place for daily recreation (Liu et al. 2021). Numerous studies (Shade et al. 2020; Evans et al. 2022) have also discussed the ability of urban green infrastructure to contribute significantly to the global mitigation of climate change and biodiversity loss, as well as positively influence food security by establishing interconnected blue-green networks throughout the cities with urban forests, green corridors, and urban agriculture. Several studies (Basnou et al. 2020; de Oliveira et al. 2022; Wang et al. 2022) on urban green infrastructure have proved to be efficient both on the local and global levels.

However, the establishment and management of urban green infrastructure has also proved to be expensive in many cases and to perform so-called disservices. Considering the cost-related barriers, land- shortage, and land use regulations in urban areas, the development of green infrastructure often happens to be spontaneous or uneven (Shi 2020; Cousins 2021). As a result, some districts become much greener, safer, and more comfortable than others. Occasionally, it is the development of green infrastructure that aggravates the spatial injustice in cities. Several cases of "green gentrification" have been already described (Anguelovski et al. 2022; Rigolon et al. 2023), when lower-middle-income districts get an intense green development and attract the upper-middle-income population that gradually effects the district's land value and average prices, forcing the former population to move about.

An even more common controversy around urban green infrastructure is a conflict between its social and ecological aspects (Depietri 2022). The efficiency of primarily social functions to a significant extent depends on their spatial justice, meaning availability and accessibility to all city dwellers, including the even distribution of green elements in the city, as well as their management and functionality. In contrast, to perform the ecological functions (including mostly regulating and supporting ecosystem services) green infrastructure usually needs large, intact areas with limited access for the population. This assumption is not always accurate.Several studies (Fahrig 2020; Varentsov et al. 2023) have discovered that small green elements can be as efficient as large ones if they are interconnected and have good quality. Nevertheless, many features of green infrastructure required for their ecological efficiency (Yao et al. 2021) differ from those required for spatial justice (Yazar 2023). It is also worth mentioning that urban residents are beneficiaries of ecosystem services, performed by green infrastructure, in any case. However, the question arises as to which portion of the urban population benefits and to what extent. For example, the existing green area can be directly used as a place for recreation, and simultaneously it provides regulating services (air purification, climate regulation). However, if this green area has limited access (e.g., it is not public) or is not big enough, then a certain part of the population cannot use it as a recreational site.

This contradicting interaction gives birth to the Spatial justice - Ecological efficiency Nexus of urban green infrastructure. Generally, one side of the nexus prevails over the other in the city, resulting in the underdevelopment of either the social or ecological side and creating trade-offs at their interaction. However, the evidence demonstrates (Valente et al. 2020; Ferreira et al. 2021) that it is possible to support a balanced nexus with just and ecological features co-benefitting each other in the city.

The concept of the nexus has gained increasing prominence in urban ecological research as a framework for understanding the interconnectedness and interdependencies of critical resource systems within cities (Escobedo et al. 2019; Kumar et al. 2019). Traditional disciplinary approaches often fail to capture the complex interactions between different urban systems, leading to unintended consequences and inefficiencies. By adopting a nexus perspective on green infrastructure, researchers can analyze the synergistic effects and trade-offs associated with urban development and green area planning, identifying opportunities for integrated solutions that enhance sustainability and resilience (Amaral et al. 2021; Lampinen et al. 2023).

Regarding this research, our hypothesis is that green infrastructure in Russian cities predominantly has an ecological aspect, meaning that it provides a large volume of ecosystem services that are still unavailable to a significant portion of the urban population. This idea is based on our previous studies (Klimanova et al. 2018; Klimanova et al. 2020; Klimanova et al. 2021) and other works (Haase et al. 2019; Murtazova et al. 2023; Konstantinova et al. 2024) for large Russian cities that revealed an uneven distribution of vegetation yet large total green areas as well as planning and monitoring issues. However, we have not studied southern Russian cities in particular. Therefore, considering the natural and planning regional peculiarities, we expect differences in the range of ecosystem services provided by southern urban green infrastructure.

In the context of Russia, the early Soviet planning for large cities mostly considered the recommendations of 10 $m^2$ of managed green area per person, 3 ha as a minimum size of a district park and 15-minute walking accessibility from the residential zone. As a result, many Russian cities have been recently demonstrating high results on green infrastructure availability, accessibility and ecosystem services performance (Matasov et al. 2020; Klimanova et al. 2021; Varentsov et al. 2023; Skachkova 2024). However, the urban population in Russia has been increasing, especially at the expense of large cities. Urbanization rate of the Southern and North Caucasian Federal Districts has demonstrated exceptional growth due to the natural increase, by 20%[1] for all cities in the region on average since 2000. Besides, the Caucasian cities are becoming more popular with tourists, meaning that the quality of their urban environment is also an essential part for the general regions' touristic attractiveness (Litvinova 2020). New residential, business and leisure areas transform the old planning and create new infrastructure patterns inside the urban zone, affecting the green elements accessibility, availability and justice. This new touristic attractiveness of the Caucasian cities also raises the question of who this new green infrastructure is for: tourists or the local population.

In this study, we focus on the relation between justice and ecological aspects of urban green areas, unlike other studies on urban green infrastructure in Russia, including our previous assessments. The aim is not to evaluate ecological and justice aspects separately, but to assess their interaction and the consequences it poses on the efficiency and overall quality of green infrastructure.

The use of remote sensing and open-source data allows us to compare and evaluate numerous parameters simultaneously and not focus on a single aspect of green infrastructure, which is generally not enough to draw conclusions about its role in the well-being of the population and its contribution to improving the urban environment. In this paper, we hope to introduce a multidimensional approach to understanding the functions and qualities of green infrastructure. We believe that these concepts will allow for a more comprehensive assessment and planning of the various aspects of green areas.

Therefore, this study aims to assess the state of the Spatial justice - Ecological efficiency Nexus in the large Caucasian cities of Russia to define the type of interaction between the just and ecological aspects of these cities' green infrastructure and the emerging conflicts or co-benefits. To meet this aim, we set several specific objectives: 1) to introduce the concept of the Spatial justice - Ecological efficiency Nexus of urban green infrastructure; 2) to develop a method to assess this Nexus; 3) to determine the prevailing aspect of green infrastructure in the studied cities.

[1]Based on data for 2023 from The Federal State Statistics Service of Russia

## MATERIALS AND METHODS

### Study Area

The studied cities (Makhachkala, Grozny, Nalchik, Maykop, Vladikavkaz, Stavropol) belong to the North Caucasian and Southern Federal Districts of Russia. They are the administrative centers of the federal subjects with a population of over 100,000 inhabitants (Fig. 1).

The temperate climate in the Caucasian region changes from mild southern in Vladikavkaz, Nalchik, and Maykop to more continental in Stavropol and Grozny, and finally to semi-arid in Makhachkala. The natural conditions of the latter may be considered the least favorable for vegetation growth; however, it was concluded in several studies (Farrel et al. 2022) that the justice and intactness of green infrastructure is not always connected to the natural conditions but to the efficient management and planning. All of these cities have either a foothill location or a hilly terrain, which makes them particularly vulnerable to dangerous natural phenomena like floods, mudflows, and landslides.

### Study design

The design of this study is based on the idea that the quality of green infrastructure is defined by numerous features that may affect each other positively or negatively or exist independently (Fig. 2). We call the interaction of two particular features in this study the Spatial justice - Ecological efficiency Nexus. Depending on the prevalence of one or another Nexus side, it may be balanced (both sides are similarly developed), or imbalanced (one aspect is significantly better developed, often at the expense of the other).

The quality of urban green infrastructure is usually defined by three main characteristics (Lindholst et al. 2016): 1) size, structure, configuration, location, and accessibility; 2) functionality and efficiency of ecosystem services performance; and 3) management, organization, and integrity. The assessment of the spatial justice of green infrastructure also depends much on these three groups of parameters, and usually it is the accessibility that is studied to the greatest extent, which is generally assessed by such parameters as the provision of a population with green elements, walking distance to them, and their distribution across the urban area (Maroko et al. 2009). The intactness, or ecological efficiency, of urban green infrastructure commonly depends on vegetation fragmentation, landscape position, connectivity, health, exposure to pollution, and species composition (Teixeira et al. 2021).

We developed a set of indicators to individually assess the ecological efficiency and spatial justice of urban green infrastructure in Russian Caucasian cities (Table 1). Spatial justice parameters consider the share, degree, or availability of 1) open public green elements; 2) green infrastructure per capita; 3) green infrastructure designed for daily recreation; 4) accessible green infrastructure in a 10-minute walk; 5) residential greenery; and 6) green infrastructure even distribution. All of these indicators are meant to describe the availability, accessibility, efficient use, and just distribution of green infrastructure in a city.

Ecological aspects include indicators that describe: 1) tree vegetation on steep slopes; 2) greenery of river zones; 3) urban tree cover; 4) protected areas; 5) green area without the edge effect; and 6) large or interconnected small green elements. These parameters define vegetation's ability to perform the most important supporting and regulating ecosystem services. For most indicators (except steep slope greenery and protected green areas) we considered only green infrastructure inside the built-up urban zone and those green elements, which are deeply incorporated into it.

Since urban area are not supposed to be 100% green or intact like natural ecosystems, optimum values (Table 1, column 3) were adjusted to the recommended values, according to scientific studies, urban planning guidelines, or expert estimations. To conduct an integrated assessment of the Nexus, all values were normalized from their primary optimum value to a 100-point scale (for example, for protected areas the primary optimum value is 30% of total urban green area, thus, if a city has 30% of its green infrastructure protected, it will score 100). Thus, for each indicator, 100 points is the maximum.


**Fig. 1. Study area**

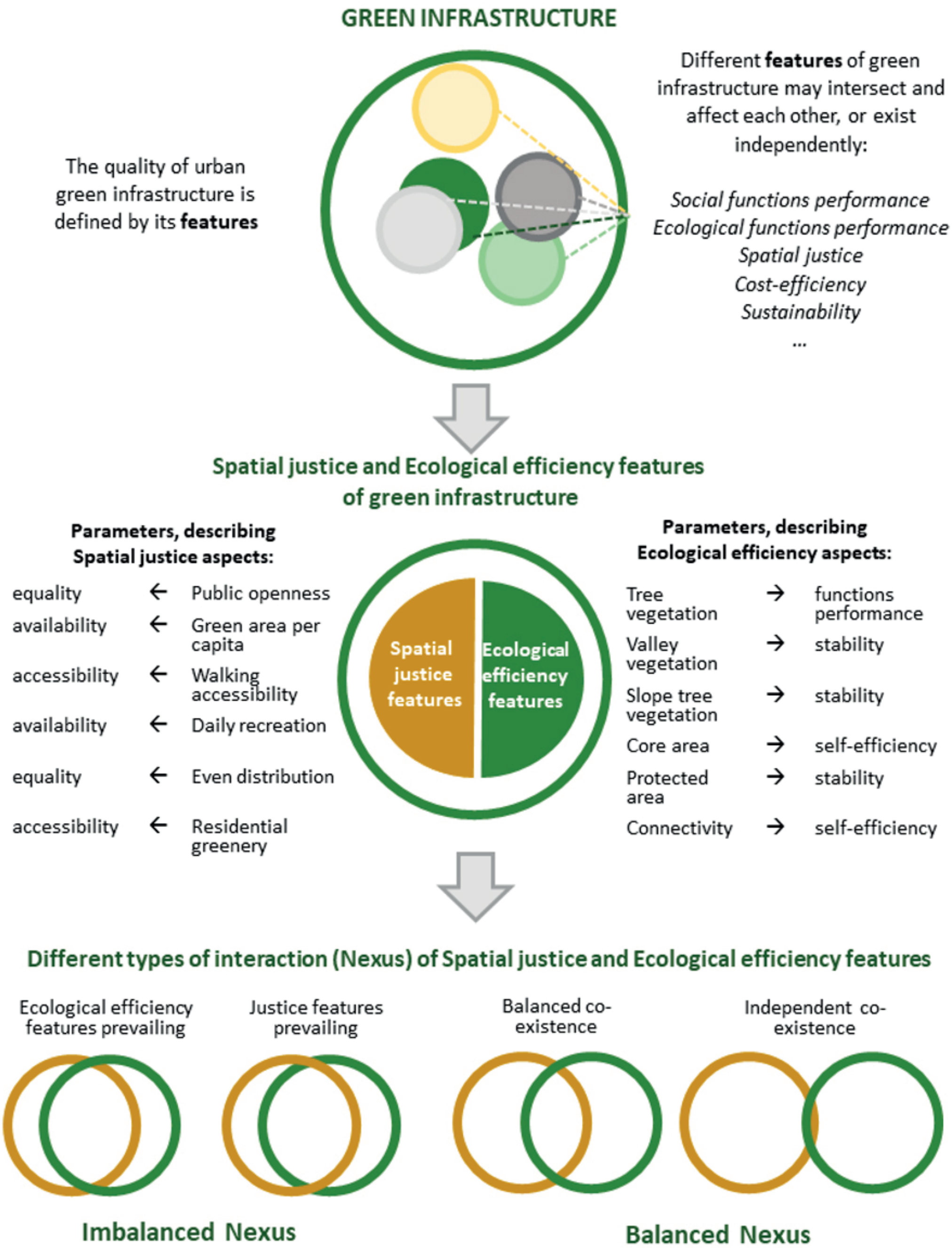


**Fig. 2. The Spatial Justice – Ecological efficiency Nexus assessment design**

Our assessment is based on various indirect indicators, such as the exposure to edge effects, the number of parks managed in accordance with general plans, and other factors from Table 1 that can be derived from publicly available data sources. These indicators provide information about the overall functionality and quality of green spaces. For example, if a park is managed for recreational use on a daily basis in accordance with its functional zoning as outlined in the general plan, we consider its management satisfactory. Similarly, we apply this logic to parks with protected status and parks that are not exposed to edge effects. These indirect indicators allow us to draw conclusions about the state of vegetation and ecological performance. However, direct assessment parameters like the age of trees, species diversity, vegetation state or visitors' activity, management arrangements, "non-green" infrastructure can give a more detailed result of the Nexus assessment.

## Data

The base for the indicators' assessment is the urban landscape models for the study areas. We computed them by combining vegetation cover raster, derived from NDVI (basing on Sentinel-2 satellite images for summers months); valleys and watersheds raster, derived from Copernicus-30 digital elevation models; urban functional zoning and built-up types vector, derived from General Plans.

## Methods

Most indicators were assessed by calculating green area for different territorial units (residential districts, steep slopes, river zones, protected areas), using the Tabulate Area instrument in ArcGIS software. Slope steepness was calculated by using the Slope instrument. We also considered slopes outside the urban core, as they pose a threat to the adjacent built-up zone. We also did not include small river valleys (with river length less than 10 km), because their influence in comparison to other indicators is less significant.

**Table 1. Spatial justice and ecological efficiency parameters of green infrastructure Nexus and their meaning**

| Spatial justice indicators | Interpretation | Primary optimum value |
|---|---|---|
| Open public green area | Share (%) of publicly open urban green area from all urban green area | 100% of all urban green infrastructure |
| Public green area per capita | Population provision ($m^2$/per.) with publicly open green area | 9 $m^2$/per. |
| Green area, designed for daily recreation | Population provision (%) with urban green area, designed and maintained for daily recreation | Basing on the standard 4 ha / 1000 per. (Jenkins et al. 2005) |
| Accessible green area in 10-minute walk zone | Share (%) of parks larger than 1 ha within the 10-minute walk from residential areas | 100% accessibility for residential area |
| Residential green area | Share (%) of green infrastructure in residential areas (excluding private sector) | 50% of all residential area (Breuste 2023) |
| Even Distribution Index | Evenness of green elements distribution, based on Pierson's criterion | 0 |
| Ecological efficiency indicators | Interpretation | Primary optimum value |
| Steep slopes forestation | Share (%) of steep slopes (>12°), covered by tree vegetation | 100% of steep slopes |
| River valleys greenery | Share (%) of urban river zones (200 m buffer from rivers longer than 50 km, 100 m – rivers longer than 10 km) covered by vegetation | 50% of urban river zones |
| Urban tree vegetation | Share (%) of tree vegetation from all urban green infrastructure | 50% of all urban vegetation (Borelli et al. 2023) |
| Urban protected areas | Share (%) of protected green area from all urban green infrastructure | 30% of all urban vegetation |
| Green area outside the edge effect | Share (%) of green area without the edge effect (140 m) | 50% of all urban vegetation |
| Green area connectivity | Share (%) of separate large (<10 ha) or interconnected small green elements from all urban green infrastructure | 70% of all urban vegetation (Bolliger et al. 2020) |

To assess the evenness of green infrastructure's distribution, we developed Even Distribution Index (EDI), based on Pierson's criterion (Eq. 1).

$$EDI = \left(N_{un} - N_{opt}\right)/N_{un} \quad (1)$$

where $N_{un}$ – is a number of nominal square units (200×200 m, a common size for a built-up block) that divide the built-up area of the city; $N_{opt}$ – is a number of nominal square units, which are optimally greened (by at least 50%).

The calculation of optimally and sub-optimally greened units (Fig. 3) was computed by using Attribute Table instruments. The square units were created by using the Grid Index Feature instrument.

The calculation of 10-minute walking accessibility was carried out with the construction of graphs on the road network. From OpenStreetMap vectors with "highway" key, we selected only those roads, which are suitable for pedestrians. For this, we chose linear features with tags "footway", "living street", "path", "pedestrian", "residential", "steps", "footway". All repeating parallel road lines were removed. Then we built a pedestrian roads graph. First, a set of linear features was converted into a single linear feature using the Dissolve tool, which was then converted into graph edges using the Features to Line tool. The graph nodes were built through the Network Dataset construction tool in ArcGIS Catalog using the calculated length of each edge. Next, we calculated the area of residential zones within a 10-minute walking distance

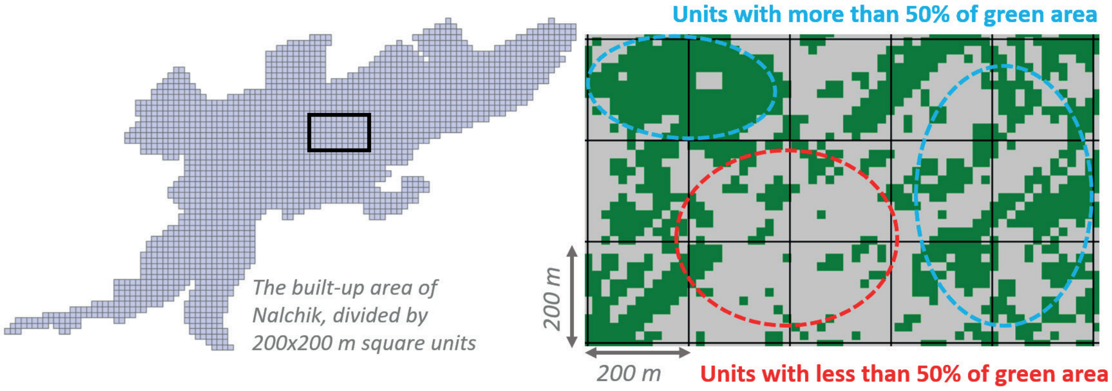



**Fig. 3. The example of greened nominal square units' calculation in the built-up zone of Nalchik**

(approximately 800 m). From the pre-digitized functional zoning scheme from the General Plans, the following zones were selected: residential private sector, residential mid-rise development, residential low-rise development, and residential multi-story development. We consider these zones as "residential areas".

We also used functional zoning to assess open public green areas and green areas designed for daily recreation. We regarded green infrastructure as open and public if it was located outside functional zones with limited access: residential private sector, engineering and utility-warehouse zones, industrial zones, zones of special public development (schools, hospitals), green areas for special purposes (military zones, airports), restricted areas, private gardens, and agricultural lands. As to the green infrastructure, designed for daily recreation, we selected green elements specifically mentioned as recreational areas in general plans (but only those, which were located close to business or residential zones) and other green elements with unlimited public access, located inside residential and central business areas with an area of more than 1 ha.

To conduct an integrated assessment of the Spatial justice - Ecological efficiency Nexus, we summed final normalized values separately for social and ecological parameters and compared the results to determine which nexus side dominates.

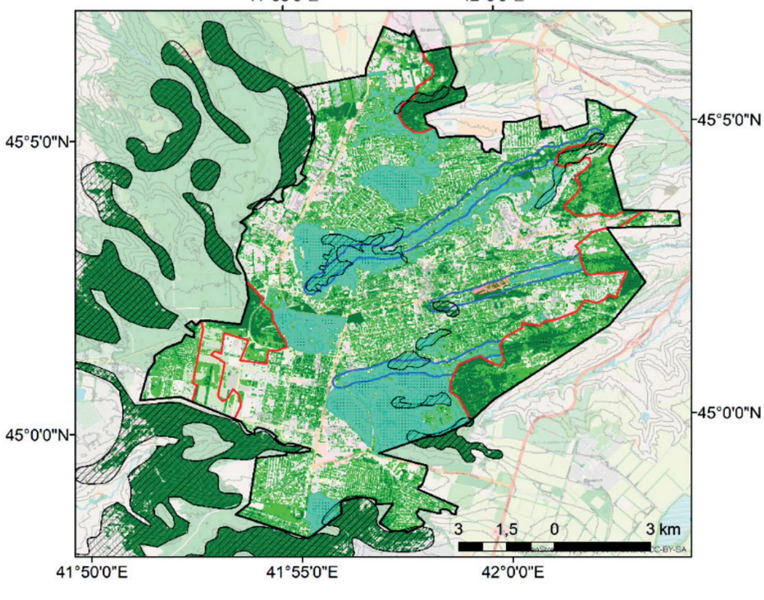
## RESULTS

### Ecological efficiency

The results show that generally green infrastructure in the studied cities has a low ecological input with a mean total score of about 300 points (max. 600). In general, Stavropol and Vladikavkaz have the most developed ecological side of the nexus, especially the first city, with almost all indicators scoring above 50 points and having a relatively high result for protected areas. In contrast, the latter city has varying ecological indicators with very low scores for areas beyond the edge effect and protected green areas. The current green infrastructure efficiently performs most of its ecological functions; however, the lack of protected and intact areas undermines its future stability and ability to do so, especially considering the growing population in the city and probable land sealing as a result. Grozny stands out among the studied cities due to its below-average ecological parameters. Especially concerning are a low forestation of steep slopes and a small share of tree vegetation inside the densely built-up zone that is important for a cooling effect during the hot summer. The two examples of a "leader city" and an "outsider city" (Fig. 4) of the ecological nexus side differ drastically from other studied cities with a score close to average (around 300). Most of them lack protected areas, green areas without edge effects and connected elements. Yet, their green infrastructure mostly consists of tree vegetation, and the steep slopes are significantly forested.

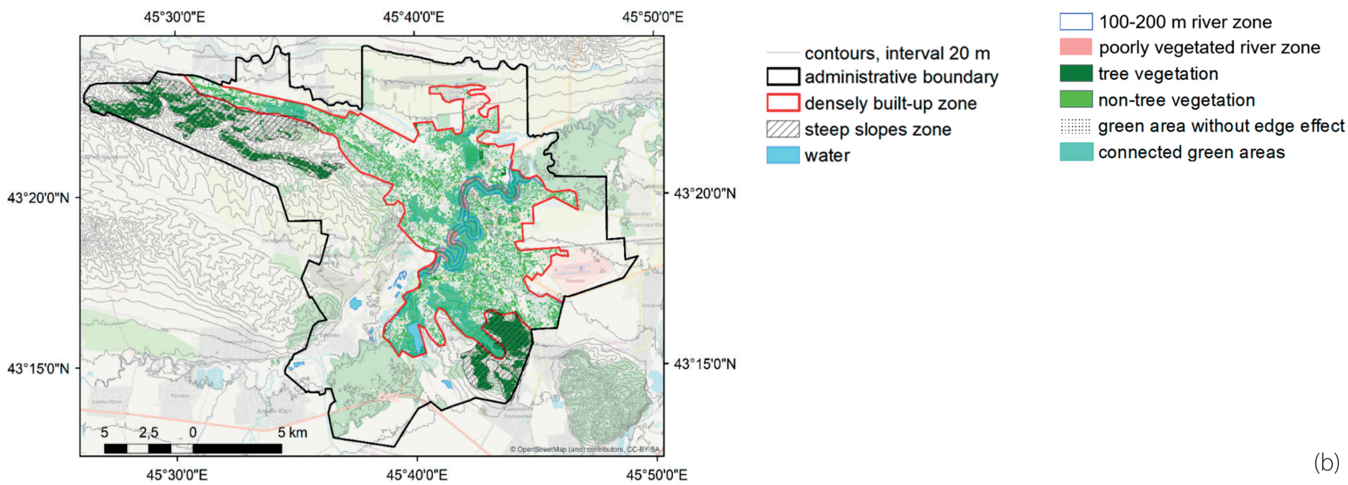
The least developed part of ecological aspect is the share of protected green areas, which is significantly less than 30% in most cities. The only exceptions are Stavropol and Makhachkala with relatively large protected areas of a regional significance (natural monuments and zakazniks[2]) within urban boundaries. A small share of green area, beyond the edge effect, is also closely connected to the lack of protected areas. Still, it is the protected areas indicator that effects the results most of all. The establishment of protected areas is a global challenge, since the goal of reaching 30% is not reached in most regions, especially in densely built-up areas. The phenomenon of large Russian cities is that by absolute estimates they are ones of the greenest cities in the world due to the relatively sparse development, Soviet planning and large areas of inconvenient for development land, like floodplains, ravines or steep slopes. Therefore, the problem of a low percentage of urban protected areas is not because of the lack of green areas in cities, but due to the opposite direction of policy instruments that aim to protect areas which are easy to protect, and to create urban green infrastructure that mostly meets social needs. Meanwhile, urban protected areas are a field that can become a compromising sphere in the Spatial justice – Ecological efficiency Nexus for its ability to evenly provide both social and ecological services for the city.

Due to the favorable natural conditions, the tree cover indicator is usually the best on this side of the nexus. Steep slopes are especially well forested in most case studies (by 70% on average), meaning that erosion control and landslide risk prevention functions are performed efficiently by urban green infrastructure. This is an important interconnection with the social sphere of the nexus because these functions directly influence the safety of the population living at the foothill.




(a)

[2]State protected areas that are generally similar to IUCN protected areas categories III, IV and V.




(b)

**Fig. 4. Ecological efficiency parameters of the "outsider city" – Grozny**

The greenery of river zones is also relatively successful in this regard (around 60% of river zones is vegetated), and the largest urban rivers generally have parks as their embankments. Compared to other Russian cities, our finding is an outstanding result, considering that many large cities have concrete main embankments with little vegetation or unmaintained parts. Yet, despite being green and well-maintained, river zones in the studied cities have few connections to urban green elements. Besides, the indicator for large and interconnected small elements is low (less than 40% of green area is interconnected or form large patches), with most vegetation concentrated in residential areas and a few disconnected, though large, parks. River zones are practically the largest green corridors in the studied cities, which paradoxically mostly perform a social role by providing public green areas rather than connecting other green elements. This is an important point of contact for social and ecological aspects of the nexus and a potential for ecological improvement, because by connecting nearby parks and unmanaged green patches to the green river zones with boulevards and corridors, the total interconnectivity of urban green infrastructure can increase significantly, thus making it more stable, resistant, and self-sufficient.

## Spatial justice

Generally, the social side of the nexus is developed better, scoring on average 390, with one indicator (green area per capita) reaching the maximum value in every city. Even though we consider only the open public green infrastructure inside the built-up area for this parameter, it is still green enough to meet the WHO standard of 9 $m^2$/per. Moreover, the lowest absolute value in Makhachkala is still almost three times higher than this recommendation. This indicator demonstrates that overall, green elements are available for the North Caucasian cities. On the whole, the green infrastructure inside urban built-up areas is, on average, 60% open and accessible to the entire population. To increase clarity, use active voice: Private households and gardens, which constitute between 40% and 70% of all green areas with limited access, primarily restrict access. Industrial greenery does not occupy much area inside the built-up zone, and other types of green infrastructure with limited access are usually located outside the urban built-up zone. This result suggests that a rare provisioning function within urban green infrastructure in large Russian cities plays a significant role. Since private greenery is often used for agriculture, we may speculate that about 20% of urban green infrastructure inside the built-up zone is capable of performing a provisioning service, which is a crucial point for the social side of the nexus.

Other residential areas, excluding the private sector, are on average 30% green, with the worst results (about 20%) in cities with the old densely built-up districts (Maykop, Vladikavkaz). It means that a considerable share of the population receives a number of ecosystem services daily, and the environment of their living is being constantly regulated by vegetation. Yard vegetation (house-side trees, flower beds, yard lawns and bushes) forms places for daily recreation; however, it offers a limited variety of recreational services. Thus, other green elements, like parks and public areas, should be considered to assess the green infrastructure's potential for providing daily recreation. Besides, this indicator allows one to see how much green infrastructure is maintained and managed, which is important for its social efficiency. On the whole, the population is well provided with green elements for this kind of activity. The only outsider is Makhachkala, which has managed green elements for daily recreation within the urban built-up zone, meeting only 40% of the population's needs. The social justice of urban green infrastructure and its services are also assessed by their proximity to users. The assessment has revealed that 10-minute walking accessibility to urban parks with an area of at least 1 ha from residential areas (excluding private homes which are far from public green spaces) is among the least developed social parameters of the nexus. On average, only 50% of residential areas in the studied cities have public green spaces within walking distance. This result demonstrates that green infrastructure's availability is not a problem for most cities, but its accessibility is. Despite being well provided with open and functional green elements, their location is not evenly distributed for all districts and populations. This conclusion is also supported by low values of the Even Distribution Index, which demonstrates that the current vegetation distribution model does not even half coincide with a perfectly even model. For most cities, the EDI value is about 0.8. Unlike most northern cities in Russia, the greenest parts here are not concentrated on the outskirts or in the river valleys, but in the private sector and health resorts. There are also cases when EDI values for the same types of residential areas in one city drastically vary. It means that greening depends not only on the planning and configuration of development but also on the quality of greening in the specific area.

It is worth mentioning that high values of this social parameter shall not necessarily conflict with the ecological parameter of large and interconnected small elements, because even distribution does not necessarily mean solely fragmented vegetation. The current green distribution model in most cities studied presents a mosaic of several poorly connected, well-green districts and those with little vegetation. The most even and optimal model can be found in Stavropol, where three large urban forests play the role of the main green massifs in the city, and evenly green built-up areas are distributed throughout the urban area.

In general, green infrastructure of all studied cities can be considered to be socially efficient, except for Makhachkala (Fig. 5), which has relatively low scores for all parameters (below 50). The best results are demonstrated by Stavropol and Nalchik, having the most available, accessible, and evenly distributed green elements. This assessment does not allow us to draw conclusions on other qualitative parameters of their green infrastructure (attractiveness, vegetation health condition, etc.). Yet, planning is one of the most challenging aspect of green infrastructure organization and its current disposition in these two cities is quite favorable for organizing the optimum green model. As for the other cities, the accessibility of green infrastructure can only be improved by establishing new, though small, public green spaces in sandlots, unmanaged areas with vegetation, or significantly sealed open spaces.

## Nexus balance

The integrated assessment of Social-Ecological Nexus functioning of green infrastructure revealed that in all case studies, the social aspect of green infrastructure dominates over the ecological, and in three cities, this imbalance is quite drastic (Fig. 6). The relation between both nexus sides may be beneficial or contradictory. One of the most common conflicting aspects of Social-Ecological Nexus of urban green infrastructure is vegetation fragmentation. On the one hand, many studies confirm that large patches are better for the volume and variety of different ecosystem services.

On the other hand, the same green area, deconcentrated into smaller patches, provides services for more population and forms a more just urban environment. However, small elements happen to be more vulnerable, less resistant, and, as a result, more expensive to support and less efficient. The compromise for these two conflicting sides is green links for small patches, which is partly met in Stavropol, Vladikavkaz, and Nalchik. Other ecological parameters do not contradict that much with social parameters but rather complement them. The greenery of river zones or the establishment of protected areas benefits the social aspect, and the forestation of slopes improves the population's safety. The problem, however, is that high values of social parameters (other than green linkage) do not usually positively affect the ecological side of the nexus. In other words, high ecological efficiency can improve the social aspect, but high social development cannot dramatically increase the ecological efficiency of green infrastructure. Ecologically inefficient green infrastructure gradually affects the social side as many services become unavailable. It can be said that the bigger the gap between the ecological and social sides is, the more contradictory the relation between them gets.

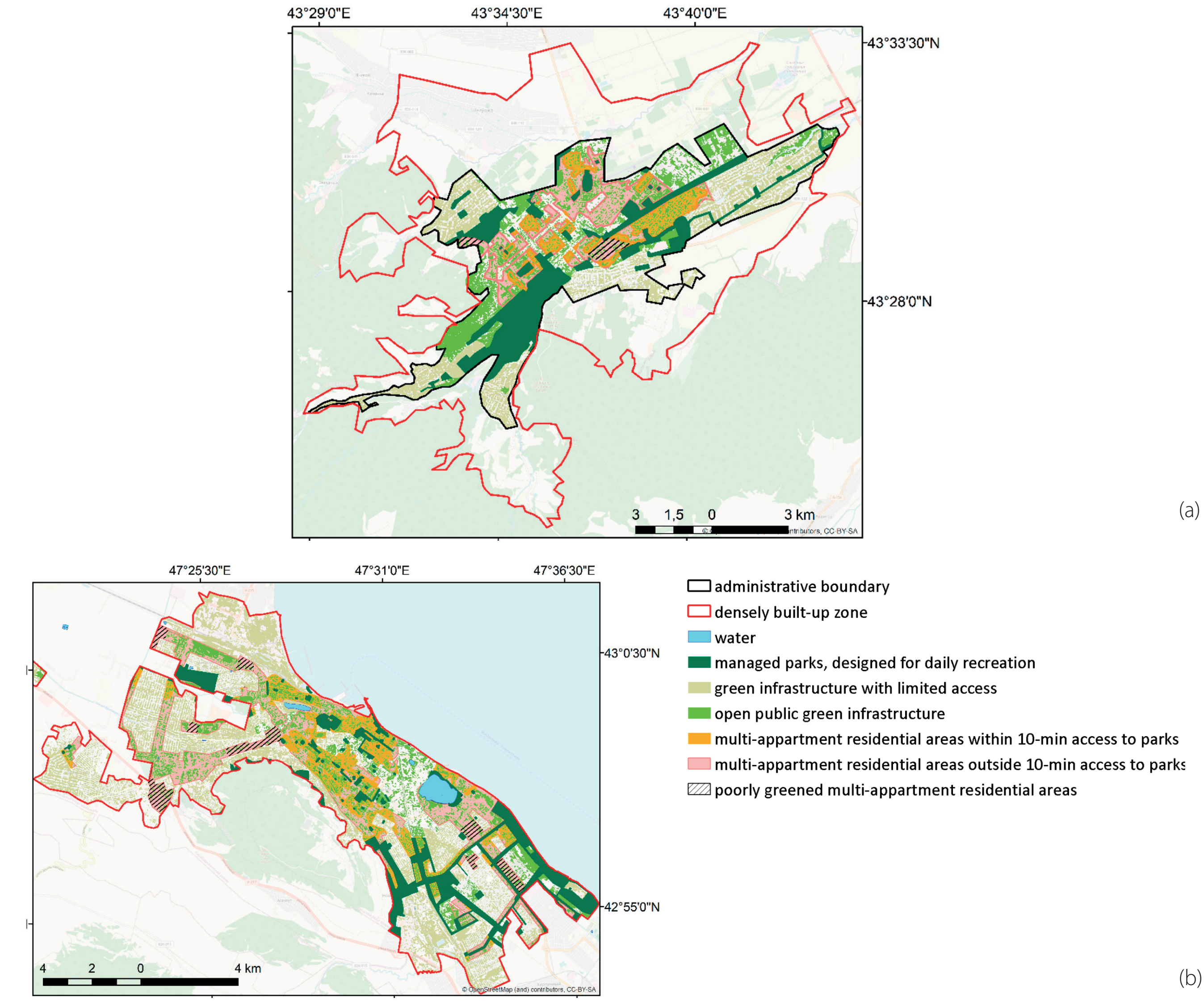



**Fig. 5. Spatial justice parameters of the "outsider city" – Makhachkala**

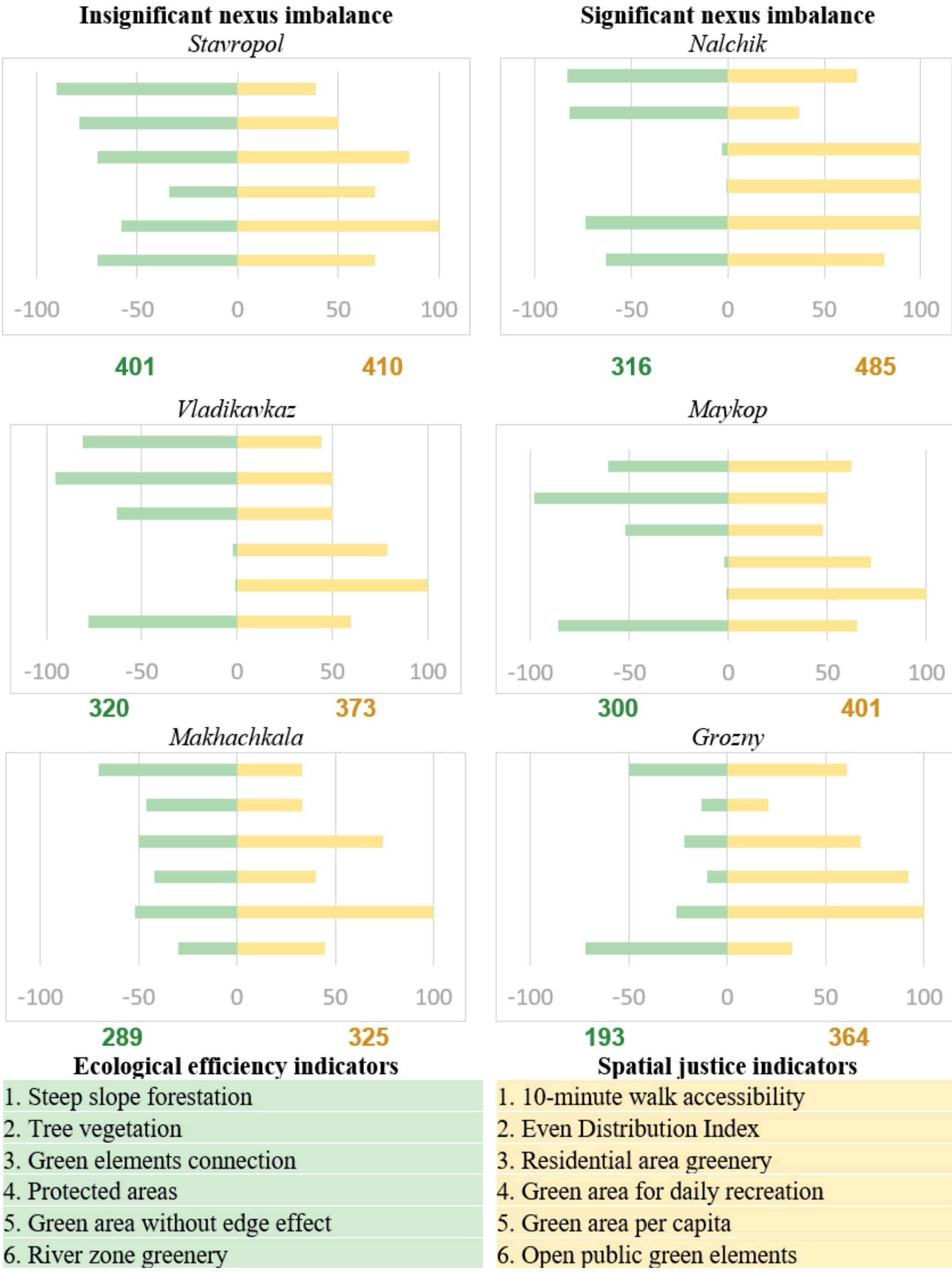



**Fig. 6. Integrated assessment of the Spatial justice – Ecological efficiency Nexus in the studied cities (the numeration of diagram bars correlates with the numeration of indicators in the legend)**

The most balanced nexus among the studied cities is found in Stavropol, with both sides scoring above 400 points and being equally developed. In Nalchik, Maykop, and Grozny, the social side of the nexus overwhelms the other one by more than 30%. This imbalance demonstrates that the urban population is currently more or less fairly provided with green areas, and all districts have a necessary amount of accessible, managed green infrastructure, but the green elements' integrity and ecological efficiency are vulnerable. The neglect of several ecological parameters, especially the lack of protected areas and green linkages, undermines the quality and availability of green spaces for future use by the population. Another case is Makhachkala, which has low results for both nexus sides. The opposite case is Grozny, with quite high scores for the social aspect but the lowest scores for ecological efficiency, meaning that its green infrastructure is vulnerable and its functioning is limited.

## DISCUSSION

Unlike most large cities of the European part of Russia, the studied southern cities demonstrate less ecological efficiency. This pattern is partly explained by natural conditions because cities within the semi-arid zone have less natural vegetation, especially woody, and it is more challenging and expensive to link green elements. However, numerous studies (Meerow et al. 2021; Miroshnyk et al. 2022) emphasize that the efficiency and quality of urban green infrastructure largely depend on management and planning rather than natural conditions. This is because the urban environment, whether arid or humid, creates unfavorable conditions for most plants in any case.

Yet, when comparing our results on ecological efficiency with the population needs, the amount of the available green areas appears to be sufficient, like in most other Russian cities. Besides, due to the vast green yards and Soviet planning of district parks according to the old city plans, residential areas have enough vegetation to perform climate-regulating and recreational functions for the city dwellers. These results are supported by other studies conducted for other Russian cities, including the southern ones (Danilina et al. 2021; Klimanova et al. 2021; Murtazova et al. 2023).

As a result, we can state that the green infrastructure of the studied cities shares many properties with other Russian cities, like the abundance of small district parks, green yards, and the concentration of tree vegetation on the steep slopes and in the river valleys. However, there are several crucial structural differences that make their green infrastructure distinctive regarding the Spatial Justice – Ecological Efficiency Nexus. For one, up to 50% of green area in many other Russian cities is concentrated in several large patches with an area of more than 50 ha (urban forest parks, suburban forests and agricultural lands). This structure is often responsible for better fragmentation and intactness results. Green infrastructure in the studied cities is mostly composed of small elements with an area of less than 10 ha, meaning that it is more fragmented and less connected. Besides, it is usually small river valleys that act as green corridors (Illarionova et al. 2024), and there are relatively few of them in the cities under study.

Another important aspect that affects the ecological efficiency of green areas is a lack of special protection status. This status does not necessarily mean that urban residents cannot visit green zones. Its purpose is to grant sustainable management, use and organization, and to efficiently combine different functions of green infrastructure. In fact, it can be a valid instrument to close the gap between conflicting sides of the Spatial justice – Ecological efficiency Nexus. However, our results show that most green infrastructure in the studied cities lacks this status. Despite being a promising tool for urban environment improvement, it seems unlikely that this particular parameter will be improved. According to the Resolution of the Government of Moscow dated December 27, 2024 N°. 3160-PP, urban protected natural areas were changed into urban protected green areas. The provisions of the Federal Law № 33 "On Specially Protected Natural Areas" that used to protect these areas are no longer in effect, and there is no longer a direct ban on activities that cause harm to ecosystems and their components. In the context of this research, there is a risk that other cities may follow this practice and also abolish the protected status of urban natural, thus further affecting the ecological efficiency of green infrastructure.

On the other hand, these cities are mostly low-rise and sparsely populated. Moreover, southern cities are increasingly gaining popularity as domestic tourist destinations, leading to the intensive development of recreational green elements for the city's guests.It is also a topic for further discussion and research, whether green infrastructure can be considered spatially just when developed and created primarily for tourists rather than the local population, and whether it can start green gentrification.

## Limitations and future aspects

While our study provides valuable insights into the relation between ecological and justice aspects of green infrastructure, it is important to acknowledge certain limitations. To make the research more representative, it is necessary to assess pairs of green infrastructure spatial justice and ecological efficiency parameters that directly oppose each other (e.g., path density in forest parks and forest vegetation fragmentation, parks proximity to public transport and green zones intactness; variety of green elements for recreational activities and for regulating or supporting services).

Moreover, data on biodiversity and visitor activity, data on the state of vegetation, species, plants age, inner "non-green" infrastructure, park management and other components can provide a detailed picture of the actual impact of spatial distribution and ecological parameters on green infrastructure conditions. However, to consider these limitations, a lot of data sources are needed, which are difficult to gather for several large cities. It is also worth stressing that the number of case studies is not enough to define different types of Nexus Spatial justice – Ecological efficiency in Russian cities. In this study, we roughly divide cities with a balanced and unbalanced Nexus, yet there may be more types of Nexus sides interactions. Besides, more conclusions about the efficiency of green infrastructure and suggestions for its planning can be drawn based on the prevailing and underrepresented parameters of green elements if more cities are analyzed. Future research should address these limitations by employing new data sources to assess the most suitable two-by-two opposing parameters and by including more large cities in the study.

The concept of nexus in this domain of research should also be addressed cautiously, because the application of the nexus approach in an urban green infrastructure context requires further development of different methodologies for assessing the social, economic, and environmental impacts of nexus-based interventions. Future research should focus on refining these methodologies and exploring the role of urban governance, policy, social infrastructure, and vegetation state in facilitating the effective implementation of nexus-based strategies to support a sustainable urban environment.

## CONCLUSIONS

Our assessment of the Spatial Justice – Ecological Efficiency Nexus of green infrastructure has revealed that most studied cities have an unbalanced nexus with a drastic prevalence of a social side. These high results for the social part are partly achieved because of the vast green area per relatively small population, meaning that North Caucasian cities have a lot of available green infrastructure. However, its accessibility is worse since the recommendations for the open public or recreational green areas in the walking vicinity to the residential districts are not met in most cities.

The analysis of ecological parameters has demonstrated that green elements in North Caucasian cities are mostly unstable due to the weak interconnection even along the large rivers and a lack of the protection status. The vast urban green areas mostly consist of tree vegetation (even in semi-arid Makhachkala) that can produce more supporting and regulating services for the urban environment than grasslands. However, most of these trees are under the edge effect, meaning that their state, intactness, and ecological functionality will be gradually decreasing.

The situation in the studied cities is not of the social aspects of green infrastructure prevailing at the expense of the ecological side. It is more like the current development affects more ecological functions, namely the sealing of river valleys, the unwillingness or inability to establish protected areas in the cities, and a lack of a unified planning system for the whole urban area that would consider the linkage of green elements at different spatial levels. The intensity of the current population growth and development in the urban area does not exceed the green infrastructure's potential to perform social functions yet. Besides, individual park projects and reconstructions generally positively affect the social aspect of green infrastructure. However, the neglect of the ecological side results in the cost increase and efficiency reduction of green elements that gradually lead to green injustice and shortage. ■

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