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Research Article

Carbonsequestration and provision of green infrastructure in the Ukrainian cities of Kharkiv and Chuguiv in the context of post-war reconstruction

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The main aspects forming the sustainability of cities in terms of provision of green infrastructure and carbon sequestration were considered. The key indicators are the part of green areas in the total area of the city (%), the coefficient of providing green infrastructure for population – CGI ($m^2.person^{-1}$) and the carbon sequestration of vegetation cover ($t.ha^{-1}$). The results of calculations are presented for the cities of Kharkiv and Chuguiv as examples of two categories of Ukrainian cities – large and small-sized, which suffered significant destruction as a result of war. The obtained results will allow to balance the green infrastructure in the post-war restoration to perform its functions.

Keywords: green infrastructure, coefficient of green infrastructure, carbon sequestration, climate chance, urban green spaces

1 Introduction

Green infrastructure is a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation, and climate mitigation and adaptation (European Commission, 2013). The importance of green infrastructure in the modern city is currently a relevant topic of research in the context of assessing its sustainability, as it ensures the implementation of such ecosystem services as air purification, soil conservation and reproduction, climate regulation, carbon sequestration, regulation of hydrological regimes of water bodies, etc. (Maksymenko & Shkaruba, 2022; Maksymenko et al., 2022b).

The authors (Zhuang et al., 2022) divide the human impact on carbon accumulation in urban green zones into direct and indirect. The first includes the change in land use, and the authors include the influence of the city's heat island effect, atmospheric pollution, and as indirect the presence of heavy metals in urban soils.

The maximum efficiency of carbon absorption by urban green infrastructure can be achieved by correctly designing the system of urban green spaces. As elements of green infrastructure can be street trees, green roofs, linear protective trees (Xi et al., 2022).

To calculate the carbon deposition in Helsinki, the authors used the "i-tree" program, which uses such indicators of stands as age, species, trunk diameter and other characteristics of urban trees and developed by the USDA Forest Service. The disadvantage of this program is that it provides approximate calculations of sequestration carbon, and the scenarios are written for the USA (Ariluoma et al., 2021).

For both: large and small cities, public awareness of the provision of green infrastructure and its ability to absorb carbon is an urgent direction of research (Lampinen et al., 2022).

Studies of the ability of urban green infrastructure to sequester carbon are closely related to the amount of green infrastructure. The issue of the availability of green areas in different parts of the city is an important area of spatial planning.

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The general attention to green infrastructure in cities is confirmed by the European Bank for Reconstruction and Development (Eurobank, EBRD) Green City Program (GCAP). It aims to achieve the following goals (EBRD, 2020) (Figure 1).

Under this EBRD program, have been identified the main systemic fields of work (EBRD, 2020) that can ensure a sustainable future for Green Cities, preserve and improve the quality of natural capital (air, water, land, soil and biodiversity), use natural resources rationally and build environmental policies that contribute to the social and economic well-being of each country. Currently, Green City action plans have been implemented in Batumi, Ulaanbaatar, Yerevan, Sarajevo, Tbilisi, Chisinau, Izmir and other cities.

We also began to study this issue in the organization of urban space in detail, taking into account the role of vegetation in:

- climate change and the forming of an urban heat island effect. Since built-up areas are usually warmer than areas with vegetation around them, it is advisable to use alternation of green and concrete areas. In this case, urban surfaces with sufficiently different heat capacities, thermal conductivity, albedo and radiation, will reduce the urban heat island effect in cities (Jacobson & Ten Hoeve, 2012; Maksymenko et al., 2021). However, turning the city into a continuous green zone is not feasible and possible. It is necessary to observe reasonable sufficiency. Therefore, the co-efficient of providing green infrastructure for population with was chosen as the main indicator that allows to state the sufficiency of green areas;
- carbon sequestration, which is actively produced by the urban environment and is one of the main gas components that create the greenhouse effect. To estimate the amount of Carbon sequestration, is used the indicator of carbon capacity, which is an important ecosystem service (Shpakivska & Maryskevich, 2009; Chernyavska & Shpakivska, 2022; Maksymenko et al., 2022a). Its value indicates the ability of the landscape to influence changes in the environment.

Thus, the aim of this work is to assess the sustainability of large and medium-sized cities in Ukraine by determining their providing with green infrastructure to perform its main environmental functions.

2 Material and methods

2.1 Study area

For this study, two fundamentally different cities of Kharkiv region were chosen: the city of Kharkiv and the city of Chuguiv (Figure 2). In official statistical sources and urban planning practice, depending on the population, there are the following groups of cities: small – up to 50,000 people, million cities – with a population of more than 1 million people (Poruchynsky & Sosnytska, 2015). Kharkiv is the second largest city in Ukraine by population. In January 2022, about one and a half million people lived there (Number of Present Population of Ukraine, 2022). The area of the city is 350 km^2. It is a large dynamic city with a high level of urbanization. Kharkiv is also the administrative centre of the Kharkiv region. Chuguiv is a district centre in the Kharkiv region. In terms of population the city is small, because the population is

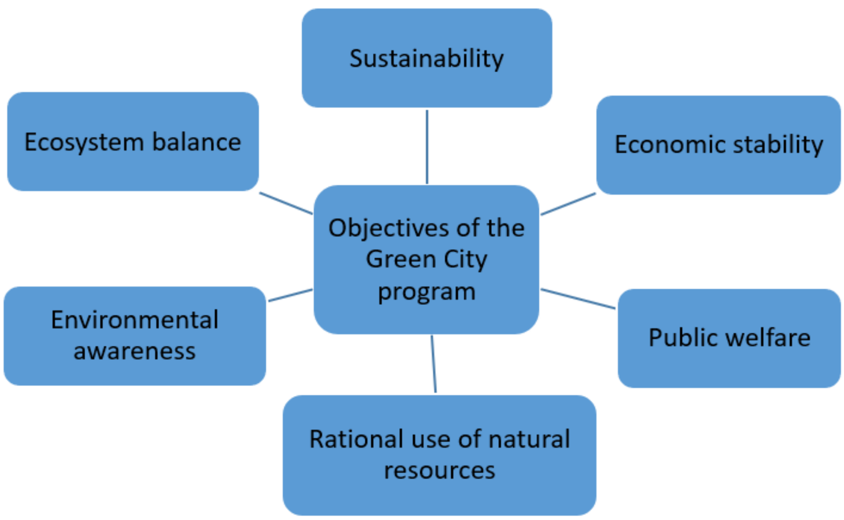

Figure 1 Objectives of the Green City Program
Source: EBRD, 2020

Figure 2 Location of the cities under study

36,438 people (Number of Present Population of Ukraine, 2022). The city has an interesting structure of both natural and anthropogenic landscapes. There have been preserved the planning and regular development of the center of military settlements on the territory of the city.

2.2 Methods for assessment of providing green space

Mathematical calculations for the provision of green space were carried out in accordance with the generally accepted assessment of the green space index as the ratio of area to the number of inhabitants:

$$CGI = \frac{SGI}{N} \quad (1)$$

where: *CGI* – green infrastructure provision factor ($m^2.person^{-1}$), *SGI* – area of green spaces (m^2); *N* – population of the territory (people)

QGIS version 3.4 and 3.22.7 with the "Field Calculator" plug-ins were used to illustrate and calculate the study area.

2.3 Methods of Carbon sequestration

The calculation of the carbon sequestration of the green infrastructure of the studied cities was carried out according to the method of authors V. P. Pasternak and I. F. Buksha "Greenhouse gas investment in the forestry of Ukraine and ways to improve it" (Buksha et al., 2003). This methodology is based on methods for assessing ecosystem services, according to P. I. Lakyda: a methodology for assessing the components of phytomass in dynamics, characterization of the main taxation indicators of dead wood, and the study of deposited carbon in the ecosystem mortmass (Lakyda, 2002).

Microsoft Excel was used for calculations. A database was created containing the results collected during field research: plantation area, plantation area divided into groups, species composition, wood regeneration, species composition index, plantation age, bonites, bonites coding (1–2 and 3–4 bonites), type of forest conditions, coefficient of the type of forest conditions, stand completeness, wood supply per 1 m^3, dead wood ($m^3.ha^{-1}$) and clutter (m^3).

Calculations were made on the basis of the collected data. Such parameters were calculated as the carbon stock of:

- plant matter – in leaves (needles), in branches, in trunk, in roots, in wood, in undergrowth, in the above-ground cover, total reserve of living phytomass);
- dead phytomass – in dry matter (crown), in dry matter (trunk), in dry matter (roots), total in dry matter, cluttering, total carbon stock in dead phytomass,
- carbon stock in the litter, carbon stock in the soil, total organic carbon stock, organic carbon stock of carbon per ha.

Calculation of carbon stock (*R*v) in living phytomass is determined by the formulas:

$$R_{v(...)} = a_0 \times A^{a_1} \times B^{a_2} \times \exp(a_3 \times A) \quad (2)$$

$$R_{v(...)} = a_0 \times A^{a_1} \times B^{a_2} \times P^{a_3} \times \exp(a_4 \times A + a_5 \times P) \quad (3)$$

$$R_{v(...)} = a_0 \times A^{a_1} \times B^{a2} \times P^{a3} \times \exp \quad (4)$$

where: *A* – age of years; *B* – bonitet; *P* – relative fullness

Carbon stock in net primary production for live phytomass was calculated by the formula:

$$V_{ag} = dGS(R_{ab} + R_{bl} + R_{us}) + \sum_i \left(dMR_i + HarvR_i + \frac{GSR_i}{Turn_i} \right) \quad (5)$$

where: dGS – net growth of stem wood ($m^3.ha^{-1}.year^{-1}$); dM – natural decline ($m^3.ha^{-1}.year^{-1}$); R^i – expressions for calculation of phytomass fractions; $Turn^i$ – time of existence of factions

Carbon stock in the undergrowth of live phytomass is calculated by the formula:

$$R_{uc} = 0.45(1.311\ P^2 + 2.561\ P - 0.0263)m \quad (6)$$

where: P – tree stand completeness; m – coefficient depending on the age of the prevailing species

The volume of carbon in the live phytomass understory was calculated by the formula:

$$R_{rg} = 0.45 k_1 k_2 K e^{k_3 \times h} \quad (7)$$

where: K – number of undergrowth individuals per 1 ha; k_1, k_2, k_3 – coefficients; h – high (sm)

The carbon content in dry dead phytomass is calculated by the formula:

$$R_{dw} = \frac{0.5kD_wN}{10} \quad (8)$$

where: k – phytomass fraction coefficient; D_w – stock per ha; N – planting composition factor

The carbon stock in the littered part of dead phytomass was determined by the formula:

$$R_d = 0.5\ kD \quad (9)$$

where: k – coefficient of dependence on species composition; D_w – stock of dead wood per 1 ha; N – coefficient of plantation composition

The volume of carbon in forest litter is calculated by the formula:

$$R_{lit} = (0.001\ H_{asl} + 4.27)k_1\ (k_2A^2 + k_3A + k_4)\ P \quad (10)$$

where: H_{asl} – altitude above sea level; A – stand age; P – completeness; k_1, k_2, k_3 – coefficients

3 Results and discussion

Chuguiv is an example of city where green infrastructure has preserved natural features and is only partially of anthropogenic origin (Figure 3).

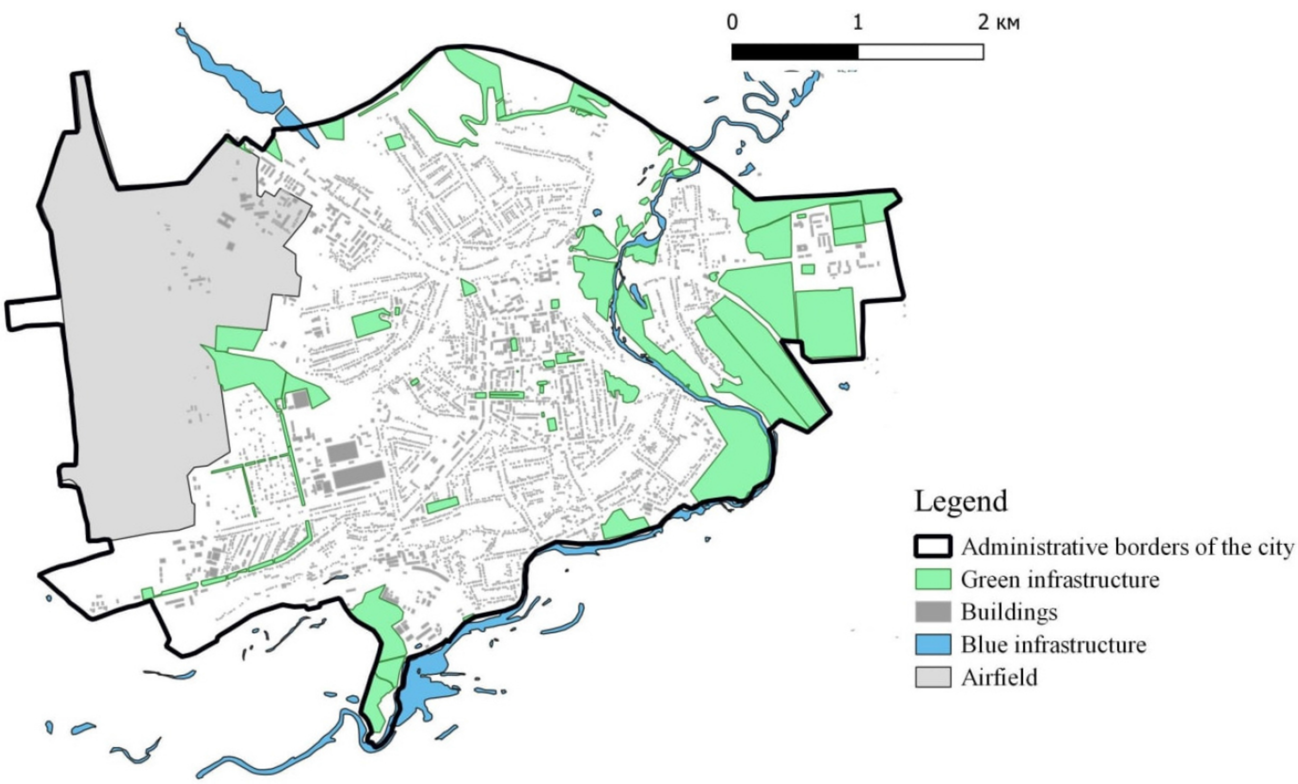

Figure 3 Green infrastructure of Chuguiv

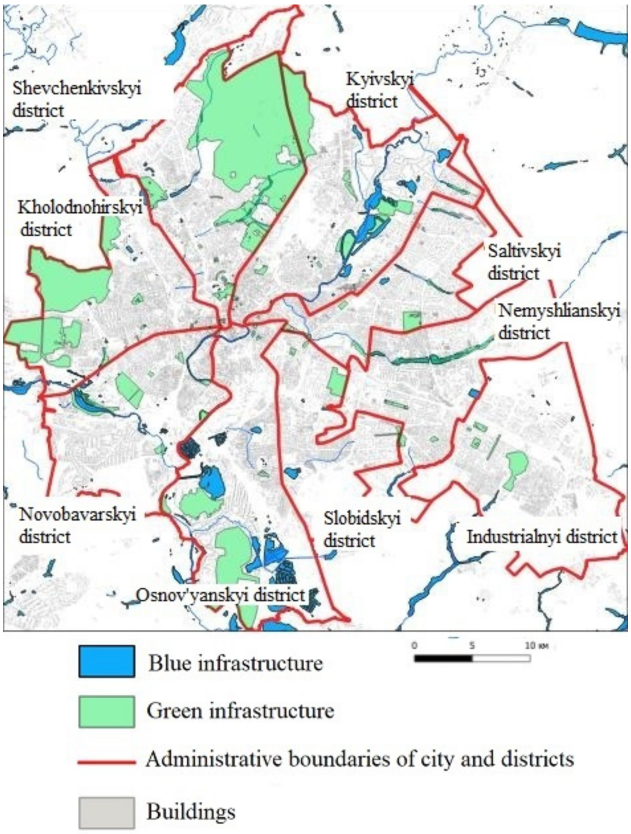

Figure 4 Green infrastructure of Kharkiv

For Kharkiv, the problem of reduction of green spaces due to construction, expansion of the transport network is relevant. Green infrastructure facilities in the city, as a rule, have no connectivity and are located fragmentarily (Figure 4).

Kharkiv is divided into nine administrative districts. Each of them has its own specifics (Figure 5). However, there is an irregular distribution of green infrastructure objects in each administrative district. Public green infrastructure is maintained by a specialized municipal enterprise "Kharkivzelenbud". Another feature is the reconstruction of green infrastructure. Most of the green infrastructure objects were reconstructed in the central districts of the city. Green areas in the housing areas of the city and on the periphery remain in unsatisfactory condition. However, there is a low level of involvement of the local citizens in the improvement of green infrastructure objects.

According to the results of the inventory of public green infrastructure objects (such as parks, squares, etc.), the area of green areas is 4,077.8 ha. The results of the degree of greening and providing green infrastructure for urban population with by administrative districts are shown in Table 1.

The highest index of CGI is observed in Shevchenkivskyi district. This is the central district of the city. There are 16 CGI objects on its territory, including a regional landscape park, a botanical garden and a large number of parks and squares. Nemyshlyanskyi and Industrialnyi districts have the lowest CGI indicators. However, a large number of residential buildings are located on the territory of these districts. Historically, these districts were built to accommodate workers of industrial enterprises that were built in the early twentieth century.

Thus, CGI for Kharkiv city is 28.6 $m^2.person^{-1}$.

The green infrastructure of Chuguiv consists of natural and semi-natural objects. A significant number of natural green infrastructure objects is due to the fact that the city was built in the valley of the Siverskyi Donets River. The green infrastructure of the city is represented by: squares, alleys, parks, boulevards, forests.

In order to assess the provision of the city's green infrastructure for such a sustainable development goal as the protection of biodiversity, an assessment of the provision of green infrastructure to the population

Table 1 CGI of each district of Kharkiv

Administrative district	Area (ha)	Area of GI (ha)	Part of GI (%)	CGI ($m^2.person^{-1}$)	Population (person)
Shevchenkivskyi	4,418.44	2,241.45	50.73	96.1996	233,000
Kyivskyi	4,569.45	1,001.7	21.92	12.1418	825,000
Slobidskyi	2,434.24	169.4	6.96	15.1674	111,687
Kholodnohirskyi	3,211.32	181.5	5.65	19.3085	94,000
Saltivskyi	2,401.24	68.3	2.84	4.6510	146,850
Nemyshlainskyi	2,229.22	32.1	1.44	2.2782	140,900
Novobavarskyi	3,471.34	75.1	2.16	4.8830	153,800
Industrialnyi	3,339.33	84.9	2.54	2.7854	304,800
Osnov'yanskyi	4,532.45	223.35	4.93	12.2586	182,199

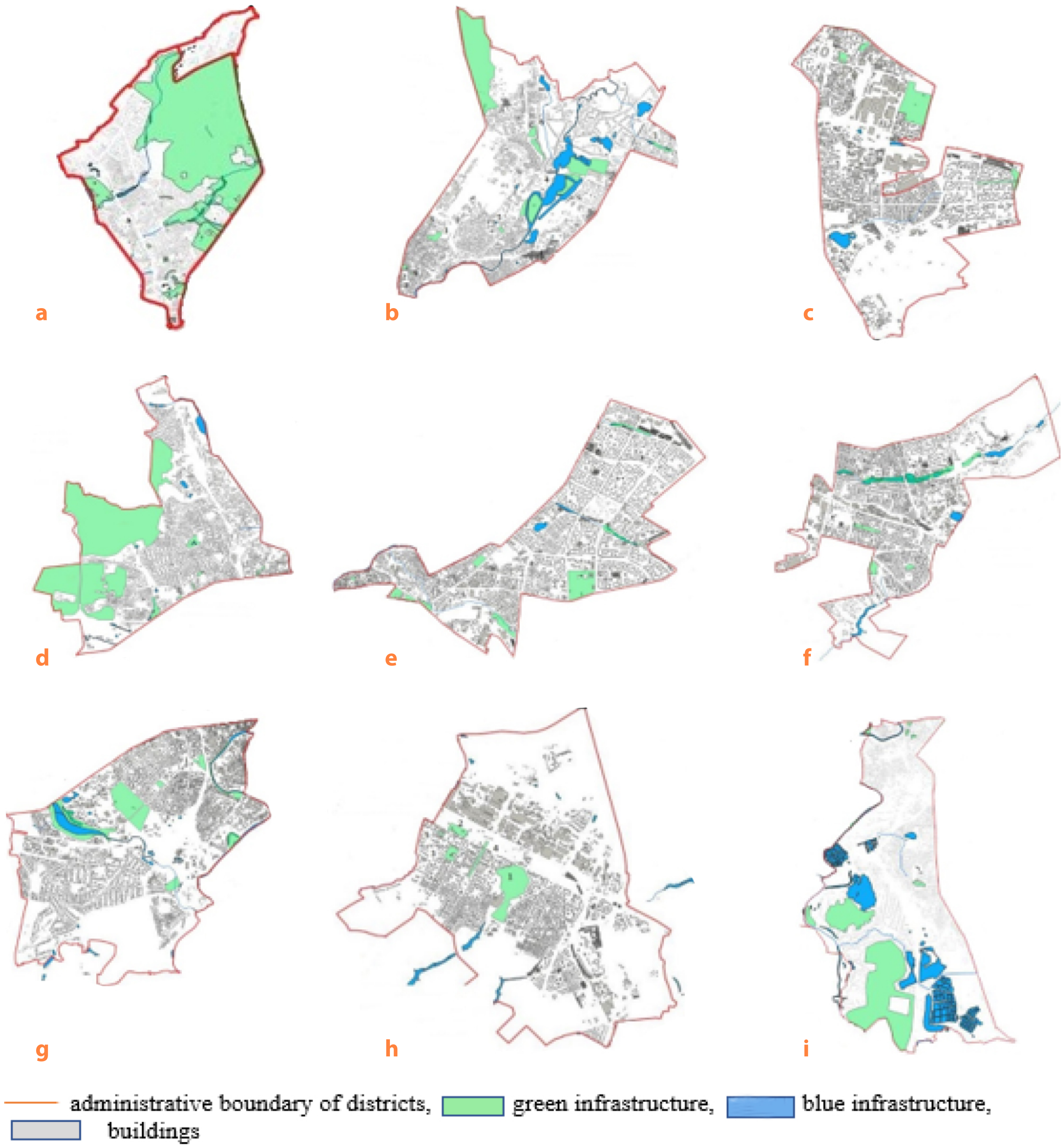

Figure 5 Green infrastructure of the administrative districts of Kharkiv
a – Shevchenkivskyi, b – Kyivskyi, c – Slobidskyi, d – Kholodnohirskyi, e – Saltivskyi, f – Nemyshlainskyi, g – Novobavarskyi, h – Industrialnyi, i – Osnov'yanski

was carried out. Since the city is small, there is no administrative division into districts, therefore the reserve calculation was carried out for the city as a whole. For this purpose, we downloaded data from the demographic register regarding the city's population and calculated the area of the city's green areas using QGIS software. For this purpose, the Calculate Geometry plug-in was used. For the purposes of these calculations, the area was calculated in km^2.

The calculation of the provision of green spaces for the population of Chuguiv was carried out by the formula (11):

$$CGI = \frac{0.86}{36,438} = 0.000023 \qquad (11)$$

Due to the area of the city is only 12 km^2, it is better to present the provision in m^2, then the provision is 23.6 m^2.person^{-1}.

Considering that according to the norm of urban greening established by the World Health Organization is 50 m^2 of urban green spaces per capita (WHO, 2012), it can be said that both cities – Kharkiv and Chuguiv need to increase the area of green infrastructure. At the same time, considerable attention should be paid to the balance of distribution of green infrastructure elements on the territory of cities (Hrechko, 2022). According to the European Commission (Green Infrastructure (GI) – Enhancing Europe's Natural Capital, 2013), both natural and semi-natural areas that are capable of providing ecosystem services can act as green infrastructure. Given the density of buildings in the central districts of the city and taking into account the number of destroyed buildings in both cities (in Kharkiv, at the time of writing, more than 6,600 buildings have already been destroyed), it is advisable to pay attention to the use of building technologies that use vertical gardening and green roofs. These techniques allow to increase the area of green infrastructure and reduce the area of "grey coatings". And this in turn will lead to an improvement in the quality of the city's ecosystem as a whole.

The city is a complex urban geosystem that must meet the needs of the population in different spectrums of life. One of these spectrums is the comfort of living, which to some extent is satisfied by green areas performing the following ecosystem services: air purification, recreation, climate regulation, adaptation to climate change, etc.

A separate type of ecosystem services provided by green infrastructure is the reduction of greenhouse gases such as CO_2 and oxygen production. It is the reduction of carbon in the atmosphere that solves a number of environmental problems and improves the quality of the environment in the city. The degree of fulfilment of this ecosystem service can be assessed by calculating the carbon capacity of the city's ecosystem.

Determining the carbon capacity for urban green infrastructure objects allows to calculate the amount of carbon accumulated throughout their life in living and dead phytomass and in the soil. In general, different tree species have different storage capacity, and the green infrastructure of the cities of Kharkiv and Chuhuiv has

Table 2 Accumulated carbon in plant matter

The carbon stock in	Accumulated carbon (t)	
	Kharkiv	Chuguiv
Leaves	0.02	0.08
Branches	0.11	0.11
Trunk	0.59	0.18
Roots	0.30	0.36
Wood	41,1516.94	19,261.48
Per ha	100.92	223.97
Aboveground	3,591.43	13.09
Ground Cover	7,173.83	60.45
Total carbon stock in living phytomass per ha	42,2279.20	19,335.03
	103.56	224.83
Littering	6,895.40	113.95
Soil	118,250.40	29.0
Total per ha	547,425.0	7,177.21
	134.25	287.09

a diverse species composition of: *Quercus robur*, *Aesculus*, *Acer platanoides*, *Tilia*, *Acacia*, *Sorbus*, *Betula*, *P. tremula*, *Alnus*, *P. sylvestris*, *Picea* and various fruit trees. But in the study, a maple (*Acer platanoides*) was chosen as a model tree for calculating the carbon capacity of green areas in the cities of Kharkiv and Chuguiv, which is a fairly common type of green spaces in Ukrainian cities.

As we use the model to unify the calculation of the carbon capacity of the studied cities, the following parameters were chosen for the model calculation: tree – maple (*Acer platanoides*), species condition index –10, age – 15, rank – 1, rank coding – 25, type of forest growing conditions – D3, completeness – 0.7, dead wood – 10, clutter – 10. The results present in Table 2.

The use of the green infrastructure concept fits well into the post-war reconstruction of the country, as this concept partially implements the goals of sustainable development. One of the visions of the post-war reconstruction of Ukraine of both the Ukrainian government and international partners is the green course, according to which one of the key dogmas is the preservation of natural capital, including biodiversity conservation, sustainable resource management, etc.

4 Conclusions

The study showed that in order to ensure sustainable urban development, it is necessary to consider increasing attention to the balance of green infrastructure as one of the key areas.

The main conclusions of the work are as follows:

1. The irregularity of green infrastructure provision in Ukrainian cities causes ecosystem services to be provided not to the full extent, which worsens the ecological condition of cities. Two fundamentally different cities of Kharkiv Region – Kharkiv and Chuguiv – selected for comparison showed that they have the same problems with green infrastructure provision.
2. Kharkiv is characterized by uneven distribution of green infrastructure facilities across the administrative districts of the city. At the same time, the CGI indicator is 28.6 m^2.person^{-1}, which corresponds to the current legislation of Ukraine. Therefore, the actual direction is to expand the green infrastructure of the city of Kharkiv, in those areas that have low indicators – Nemyshlyanskyi and Industrialnyi districts. In order to increase the area of green infrastructure, it is possible to use the territories that were used as sanitary protection zones of industrial enterprises that are now out of operation. It is also possible to revitalize the industrial landscapes of the city into technoparks, etc. using modern methods of landscaping. The stock of carbon deposited by plants in the city of Kharkiv is 134.25 t. ha^{-1}.
3. The city of Chuguiv, although at first look seems to be quite green, but calculations of the provision of green areas for citizens showed that the city needs to increase the number of green areas. This will be quite relevant during the post-war restoration of the city, as it is likely to increase the number of tourists who want to see the frontline city. Also, when calculating the model of carbon capacity in the first approximation, it was found that if the city is greened only with maples, it will be able to absorb enough carbon not to accelerate global warming. After all, the city of Chuhuiv does not have large industrial areas and most carbon is produced by road transport.
4. The use of different species and different forms of landscaping for the development of green infrastructure will increase the realization of both ecosystem services in general and carbon sequestration, which will result in positive results for both air quality and quality of living space, including recreational needs.

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