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Research article

Urban forest species selection for improvement of ecological benefits in Polish cities - The actual and forecast potential

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ABSTRACT

Trees in cities perform important environmental functions: they produce oxygen, filter pollutants, provide habitat for wildlife, mitigate stormwater runoff, and reduce the effects of climate change, especially in terms of lowering temperatures and converting carbon dioxide from the atmosphere into stored carbon. Generally, to increase the environmental benefits of urban forests, the number of trees is increased, directly influencing the canopy coverage. However, little is known about potential of modifying the species composition of urban tree communities in order to increase ecological benefits. Planting and managing trees to increase canopy is particularly challenging in city centres, where the dense, often historic infrastructure of buildings and roads do not allow for a significant increase in greenspace. Estimations of canopy cover obtained through i-Tree Canopy analysis unveiled significant potential to increase canopy cover in historical urban areas in Polish cities from 15-34% to 31–51%. This study models the ecological benefits of urban forests in Polish cities, focusing on how different species compositions can enhance environmental functions such as carbon sequestration and pollution filtration. Two main scenarios were analyzed: one involving the addition of trees based on the most common species currently planted ("standard option" SO), and another incorporating changes to the species composition to enhance ecological benefits ("city specific option" SCO). *Acer platanoides* (14.5%) and *Tilia cordata* (11.45%) were the most frequently species of Polish cities. *Betula pendula, Quercus robur, Robinia pseudoacacia, Fraxinus excelsior, Acer pseudoplatanus, Aesculus hippocastanum* and *Acer campestre* were also common species in urban forest communities (up to 5%). The diverse range of tree species in Polish cities contributes significantly to the overall carbon sequestration potential. The results suggest that modifying species composition could significantly increase carbon sequestration rates by 47.8%–114% annually, with the city specific option (SCO) being the most effective in enhancing carbon sequestration potential. This highlights the importance of strategic species selection in urban forestry practices to maximize environmental benefits and mitigate climate change effects.

1. Introduction

According to the United Nations, 55% of world's population lives in urban areas. This percentage is even higher in Europe, where 73.5% of the people live in cities. This value is expected to reach 67% by 2040, hence increased temperature coming from urban heat islands (UHI) and greenhouse gas emissions exacerbated climate change is one of the most important environmental challenges that cities will have to face in the coming years (Our World in Data, 2024). Wei et al. (2021) reported that 25 mega-cities (from 167 globally distributed cities) produce 52% of the global GHG emissions. They found that Asian cities emit the most greenhouse gasses (GHG), and most cities of developed countries had significantly higher per capita GHG emissions than those of developing countries. Climate change caused prolonged drought, heat waves and frost, rainstorms, or high winds. Their environmental, social, and economic consequences affect human quality of life including city dwellers (Short and Farmer, 2021).

Greening the urban space is one of the strategies recommended in many prominent climate change documents such as the Convention on Biological Diversity, the United Nations' Sustainable Development Goals

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(mainly Goal 11, which aims to make cities *inclusive, safe, resilient and sustainable*), and the 8th Environment Action Programme based on European Green Deal with urban environment (as a one of the priority area to *ensure high environmental protection and a good quality of life*). In turn, the European Union (EU) Green Infrastructure Strategy promotes the implementation of green infrastructure in urban areas. Green infrastructure is a relatively quick and comparably inexpensive strategy for cities to adapt to climate change and "*contributes to achieving all other objectives of the EU Biodiversity Strategy*" (COM/2013/0249) (Commission to the European Parliament, 2024).

Healthy urban forests can mitigate the impacts of environmental stresses to meet global sustainability challenges. Urban trees provide a number of ecosystem services; therefore they are an important element of liveable cities (Yin et al., 2023). Those services include environmental regulation services (e.g. air pollution reduction, temperature decrease, stormwater management), recreational services for the local community (providing recreational and tourism facilities, physical and mental health benefits), biodiversity support services (e.g. providing habitats wild fauna and flora) and supply services (e.g. food and fuel production), (Drew-Smythe et al., 2023; Kim and Coseo, 2018).

Most environmental services are related to the size and structure of trees, with older, larger and healthier trees providing a greater level of services (Suchocka et al., 2023). Additionally, some species are better than others at providing any single ecosystem service due to intrinsic (i.e. morphological and physiological) and temporal (diurnal or seasonal effects) characteristics (Pataki et al., 2021; Pukowiec-Kurda, 2022; Rau et al., 2020; Rötzer et al., 2021).

However rapid climate change has created new challenges for cities in terms of greening them. Urban trees often have to vegetate in highly degraded environments which include: i) soil degradation, ii) limiting space, iii) bad air quality, iv) heat emissions, v) water runoff and vi) susceptibility to vandalism which all affect the lives of trees in city spaces (Czaja et al., 2020). Roman and Scatena (2011) found that urban trees (mainly street trees) have high mortality rates and low average lifespans.

Biodiversity of urban forest is one of the crucial factor of environmental functionality. While cities have a high species richness, tree population is usually dominated by a few species. Research conducted in 108 cities around the world showed that 20% of trees in urban forests belonged to the same species, 26% to the same genus, and 32% to the same family (Kendal et al., 2014). Locally, single species may be even more dominant. *Tilia x europaea* is one of the most frequently planted tree species in Nordic cities (16% on average), and over 44% of street and park trees in Helsinki (Sjöman et al., 2012).

The dominance of a small number of species could be problematic along streets and other paved areas. The trees growing there are particularly exposed to the negative effects of human activity: there are heating networks in the ground, which cause an increase in temperature and contribute to the drying of the land and a decrease in water availability, concrete-covered surfaces cause significant surface runoff; a dense network of buildings prevents air exchange and increases the risk of pollutants affecting trees (Czaja et al., 2020). Good samples are historic districts in cities are typically heavily built-up and paved. The public spaces of streets and squares are small and usually intended for pedestrian traffic, catering services and cars. Therefore, there is little space for green infrastructure and the change in the structure of public space resulting from reduced car traffic is very slow. Moreover, there is little research on the role of trees in the oldest parts of cities (Mizgajski et al., 2023). Barona et al. (2022) emphasize the need to place greater focus on integrating diversity into research design in order to enhance the sustainability and resilience of urban forests. To improve the quality of tree cover, cities may focus on investments in one area (e.g. increasing forest cover, replacing paving stones with biologically active surfaces, investing in the so-called blue infrastructure), or increase the scope of work, taking into account an interdisciplinary approach to circularity of urban spaces with the support of IT solutions. Analyses by Prebble et al. (2021) indicates that at level of local government policy may use big data on urban trees and tree canopy percentages to create parameters for complex digital models as elements of urban forest management. One of the most frequently studied ecosystem services of trees is the sequestration and storage of carbon dioxide. There are several methodologies and geographic information system (GIS) models for carbon estimating in in aboveground biomass (i.e. ground sampling allometric equations, Urban Forest Effect (UFORE), CUFR Tree Carbon Calculator (CUFR Tree Carbon Calculator, 2024) and iTree (Nowak, 2021), MOTTI stand simulator (Bianchi et al., 2024) (AGB), (Habib et al., 2023). Zhuang et al. (2022) propose implementing novel and improved remote sensing (RS) techniques (e.g. hyper-spectral, Light Detection and Ranging LiDAR or carbon satellites) for carbon storage modelling. The iTree Eco model was used by Zhao et al. (2023) to estimate the ecological benefits of urban forests in: carbon sequestration, oxygen release, energy saving, rainwater retention, and air quality improvement.

The main goal of the research was to better understand the potential of tree communities growing in the historical/central districts of the 15 most populated Polish cities to perform environmental functions. The network of cities in Poland is highly diversified territorially, which results from the historical differences in the processes of its formation. The southern part of the country has a well-developed network of medium and large cities. In turn, the western and northern parts are characterized by a well-developed network of small towns. In the most urbanized voivodeship, city residents constitute as much as 79.0% of the total population, and in the voivodeship with the lowest urbanization rate - 40.5%. This differentiation is clearly visible in the oldest, historic districts of Polish cities. The oldest of the surveyed ones (Kraków, Wrocław) were built in the Middle Ages, the youngest - Gdynia, was built in the 20th century. The cities are typical for the Central European region (but both eastern and western influences are visible), hence they can be good indicator sites for almost all regions of Europe. The first part of research focused on iTree Canopy analyses the selected area covered by trees. At this stage, the gain was to determine the potential of historic districts to increase tree canopy cover. In the second part of the study, the species composition of tree communities inhabiting individual cities (“city specific option”SCO) and the degree of similarity between them were estimated. At the same time, based on the average number of tree species growing in cities, the 20 most abundant species were selected ("standard option"SO). The third part goal was comparison the potential of individual tree communities for ecological benefits (air pollution removal, water retention, carbon storage) with main focus on carbon sequestration, taking into account the time necessary to achieve increased carbon storage potential.

On the base research gains, authors formulated following hypothesis: *There is potential to significant improve ecological benefits within historical district of cities by increasing tree canopy coverage based on the most common species or modifying the current species composition.*

The research may give also input to urban tree management practice through selecting suitable tree species and provides a standardized method for assessing tree canopy cover, which is crucial for urban planning, environmental management, and decision-making processes related to urban forestry in such specific spaces such historical city districts.

2. Materials and methods

2.1. Overview of the study country

Poland is located in the northern and eastern hemisphere, in mid-latitudes, between 49°00′ and 54°50′ northern latitude, and between 14°07′ and 24°09′ eastern longitude. The country is located in the central part of Europe, mostly in the Central European Lowlands, which includes the Polish Lowland. The territory of Poland stretches from the southern shores of the Baltic Sea to the Carpathians and the Sudetes.

The length of the growing season in Poland is approximately

190–200 days in the central, lowland part of the country. In the mountains and the Suwałki Lake District, the growing season is shorter, approximately 180 days. The growing season begins at the earliest near Wrocław, and its length is 299 days, and at the latest in Suwałki, where it lasts about 200 days.

2.2. The research sites selection

There are 979 cities in Poland, 302 are independent urban communes, including 37 cities with a population of over 100,000. 61.1% of Poland's population currently lives in cities and this number is projected/predicted/forecast increase to 66.4% in 2040. The 15 largest cities in Poland in terms of population were selected for research, (Table 1).

The research areas were selected in the central, oldest parts of cities, which are traditionally heavily built-up. Old town districts with medieval origins were selected, as well as city centres created as a result of urbanization processes in the 19th and early 20th centuries. The size of the designated areas ranged from 101.93 ha (Gdynia) to 818.00 ha (Warsaw) and depended on historical conditions (Table 1). A characteristic feature of such an area is the concentration of architectural monuments, including churches, the town hall and historic tenement houses, which have been an inseparable element of the landscape for centuries. The boundaries often coincided with the medieval urban layout of the Old Town. In many cases, these were the lines of former defensive walls, which today can be marked in the lower parts of the buildings or preserved in the form of fragments of fortifications. Natural boundaries, such as rivers and steep hills, also marked the boundaries. The characteristic urban layout was also taken into account - narrow streets, often irregular roads and squares, which were the center of social and commercial life. The surface of these streets often retains its former, historic character through cobbled stones. Parks were excluded from the research.

2.3. I-tree canopy procedure

Coverage assessment was performed using i-Tree Canopy, one of the iTree tools. i-Tree is a suite of computer programs, which was originally developed in the 1990s as the Urban Forest Effects model (UFORE), and with a street tree assessment tool (STRATUM) added in the early 2000s. Currently, i-Tree has different tools that are used to estimate urban and rural forest structure, ecosystem services, values, and risks related to forests and people (Nowak, 2021). i-Tree Canopy uses Google Maps/Google Earth imagery data (with a resolution of about 0.3 m) of the survey area to produce statistical estimates of tree canopy and other types of land cover such as lawns, buildings and impervious surfaces (e.g. roads) using point interpretation. With i-Tree Canopy, is possible review Google Maps aerial photography at random points to conduct a cover assessment within a defined project area.

The i-Tree Canopy analysis was performed following steps.

i) The polygon boundaries of the investigated areas (or areas of interest) were drawn;
ii) The cover classes used for the assessment were defined using a common land cover classification scheme suggested in i-Tree materials and encompassing the land cover types of interest present in the studied area (https://canopy.itreetools.org/classes): T (Tree/Shrub); H (Grass/Herbaceous), IB (Impervious Buildings), IR (Impervious Road); IO (Impervious Other); W (Water); S (Soil/Bare Ground)
iii) 1000 random points were placed within the area of interest and then were identified by land cover class. Statistical estimates of the area in each coverage class (in percent) were calculated as (Nowak, 2021):

$$\% = n / N \quad (1)$$

where:

n = number of points hitting the cover class,

N = total number of points analyzed among all cover classes (1000).

The standard error (SE) was calculated as:

$$SE = \sqrt{(pq/N)} \quad (2)$$

where:

$p = n/N$

$q = 1 - p$

Percentage tree cover was multiplied by the area analyzed to determine the total tree cover area. In this way, the actual state of the area covered with tree canopy was determined ("actual cover")

iv) 500 additional random points were placed in the selected area. The points were assessed for possible tree cover. If it was decided that it would be possible to plant trees at a given point, the point was marked as a tree canopy. Then, all 1000 points determined in the previous stage were analyzed again. If it was considered that

Table 1
The characterization of selected cities.

Name of the city	Population size [citizens]	Annual concentration of air pollutants [μg m^{-3}][b]					Estimated area [ha]	Average annual temperature [°C][A]	Average annual precipitation [mm][a]	Length of growing season [days]
		NO_2	O_3	PM2,5	SO_2	PM10				
Bialystok	296,401	12	46	13	1.8	21	279.82	7–8	500–650	272
Bydgoszcz	341,692	23	45	13	2.3	23	194.43	8–9	500–650	298
Cracow	780,796	21	39	18	5.0	30	394.62	8–9	700–800	298
Czestochowa	215,905	31	52	–	6	33	263.56	9–10	500–650	298
Gdansk	470,633	17	51	14	2.0	20	162.59	8–9	500–600	300
Gdynia	244,104	9.2	56	15	2.7	19	101.93	8–9	500–600	300
Katowice	289,162	46	45	21	6.5	31	367.19	9–10	750–850	298
Łodź	667,923	19	56	13	3.5	18	438.49	8–9	500–600	298
Lublin	337,788	17	46	20	5.6	25	353.00	8–9	500–650	297
Poznan	530,464	26	41	16	4.2	22	299.10	9–10	500–650	299
Radom	208,091	18	45	18	1.9	26	157.09	8–9	500–650	298
Rzeszow	198,476	27	48	20	2.4	32	260.14	8–9	700–800	299
Szczecin	396,472	12	52	12	5.2	20	276.48	9–10	500–650	299
Warsaw	1,792, 918	41	45	17	1.8	35	818.00	9–10	500–650	298
Wroclaw	641,201	44	47	20	5.3	24	296.14	9–10	500–650	299

[a] – source: Polish Climate maps– climatological characteristics of selected meteorological elements in the Polish area, based on information from the Central Historical Database of IMGW-PIB https://klimat.imgw.pl), data collected from 1991 to 2020.

[b] – source: Chief Inspectorate for Environmental Protection in Poland (https://powietrze.gios.gov.pl/pjp/archives), data collected for 2022.

it was possible to plant a tree at a given point, the cover status was changed to "tree cover". In this way, the potential cover of each area with tree canopy was determined ("potential cover").

2.4. Estimates of air pollution removal, carbon sequestration, and hydrologic impacts by investigated areas

Air pollution removal, carbon sequestration, and hydrologic impacts were estimated based on the area of tree cover estimated in i-Tree Canopy. A local standardized air pollution removal rate (e.g., kg/m2 of tree cover) was multiplied by local tree cover (m^2) from i-Tree Canopy to estimate a total effect from the trees (kg), (Nowak, 2021). Assessment of carbon storage and annual sequestration were based on U.S. data and methods described by Nowak et al. (2013). Standardized value of carbon storage per area of tree cover (7.69 kg C/m^2) were applied to the tree cover amount to estimate carbon storage. State-specific values (kg C/m^2 tree cover/year) were used to estimate carbon sequestration. Standard errors of removal and benefit amounts were based on standard errors of sampled and classified points. Avoided runoff, transpiration, and rainfall interception removal rate (e.g., m^3 water/m^2 of tree cover) was multiplied by tree cover (m^2) to estimate a total effect from the trees (m^3), (Table 2).

2.5. Assessment tree species diversity

Data obtained directly from the Environmental Departments of City Halls were used to study the tree species diversity in Polish cities. These were internal official documents in Polish language prepared on the basis of internal reports regarding the number and species of trees growing on individual streets. Based on these documents, a summary of the qualitative and quantitative tree species diversity in each of the studied cities was establish. These data were also used to select the species that were most abundant in all cities (average data).

Two kinds of communities were defined and selected to assess the comparative ability of tree communities to sequester carbon dioxide.

- "standard option (SO)" was selected on the basis of the 20 most numerous trees in cities in Poland. In this option, the share of individual trees species was constant.
- "city specific option (SCO)" was characteristic of the unique tree community for each of the studied cities. In this option, the share of individual tree species varied depending on the location.

2.6. Estimation of carbon sequestration by specific tree species communities

To annual estimates of carbon storage by individual tree species, the standard i-Tree carbon equations based on an estimated annual growth rate (Nowak, 2021). These values varied based on length of growing season (Table 1). Length of growing season, species, crown light exposure and tree condition are the drivers of annual DBH growth which allows for estimation of carbon sequestration. Data are available form iTree Database (Nowak, 2021).

For the calculation of tree numbers in dependence on carbon storage C potential of individual tree species in the community was used, by taking into account the percentage share of individual species. It was calculated as:

$$CF = Cpa/\sum Ci \quad (3)$$

where:

CF - Factor of C storage for specific age of tree.

Cpa - C storage potential value of whole area.

$\sum$Ci - sum of C storage of individual tree species in dependence on age of tree

$$T = R \text{ x } CF \quad (4)$$

where:

T - number of trees.

R – ratio of specific tree species in community [%]

Table 2
Removal rate of benefits of tree coverage estimated by i-Tree Canopy (Hirabayashi, 2016).

Abbreviation	Description	Removal rate (g/m^2/yr)
Annual Air Pollution Removal Benefits		
CO	Carbon Monoxide	0.114
NO_2	Nitrogen Dioxide	2.616
O_3	Ozone	11.647
PM10	Particulate Matter greater than 2.5 μm and less than 10 μm	3.309
PM2.5	Particulate Matter less than 2.5 μm	1.625
SO_2	Sulfur Dioxide	0.942
AVRO	Avoided Runoff	62.728
E	Evaporation	355.280
I	Interception	356.346
T	Transpiration	240.445
PE	Potential Evaporation	754.281
PET	Potential Evapotranspiration	581.273

2.7. Statistical analysis

Ward's Hierarchical Clustering Method (TIBCO Statistica® ver.13.3.1) was used, for analysis of variance approach to estimate the Euclidean distance between clusters. This technique using amalgamation methods based on calculated distances/similarities between objects (number of specific trees in each community) created assigns objects to groups (clusters). Groups were similar with respect to the considered segmentation variables (homogenous groups). The number of clusters was determined according to Bakker (2024). The procedure made it possible to determine the mutual similarity of tree communities, taking into account the specificity of the site "city specific option (SCO)".

3. Results and discussion

3.1. Urban tree canopy cover evaluation

The urban tree cover (UTC) is essential for supporting ecosystem services and maintaining healthy urban environments (Tonyaloğlu and Atak, 2021). Research conducted in selected areas of 15 Polish cities showed that tree canopy coverage ranged from 15.28% to 34% of the total area (Fig. 1). For comparison, Nowak and Greenfield (2018) estimated that in the US average tree canopy cover is equal 39.4%, less in Florida, where the median canopy coverage was 32.3% (Salisbury et al., 2022). In turn, other green areas (mainly lawns) occupied from 5.01 to 11.62%. The research confirmed that in city centres and especially in historical districts, the most land area is taken up by buildings (up to 39.7%) and roads (up to 24.2%). Other places identified as impervious occupied from 11% to 20.88% (Fig. 1) of the land area. Dense development in historical centres contributes to the lack of space for planting trees. Mizgajski et al. (2023), analyzed the occurrence, density, species composition and spatial distribution of trees in the oldest parts of Poznań, Lublin (Poland) and Lviv (Ukraine). Based on historical documents (from the 17th century), he concluded that trees were planted in home gardens and squares. However, the streets were usually devoid of tree plantings and the greenery cover did not exceed 5%. However, in our study, we did not find a clear correlation. An example is Wrocław, a city with the lowest tree canopy cover does not have the highest percentage of buildings (Fig. 1). The accuracy of the measurement depends on the methodology used. The models used always contain errors. National Land Cover Database (NLCD) underestimates tree canopy in urban areas by 9.9% compared to estimates derived from high-resolution

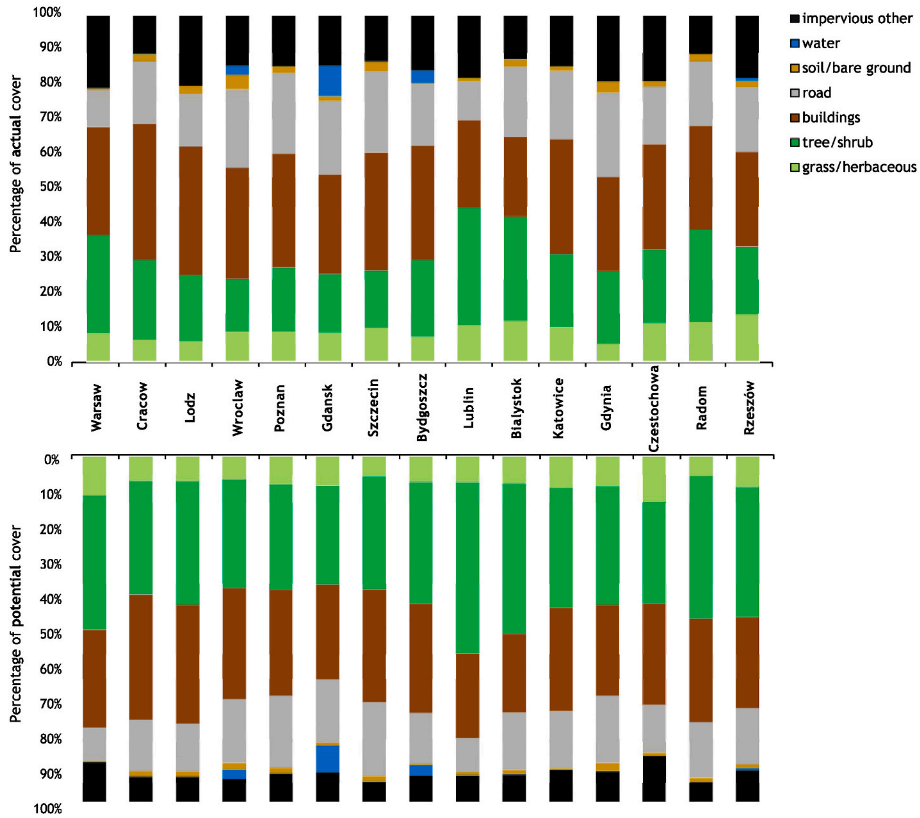

Fig. 1. Actual and potential tree canopy cover within Polish cities.

datasets (Heris et al., 2022; Greenfield and Schleeweis, 2023). Human intelligence (HI) estimates of urban tree canopy were higher (31.5%) than artificial intelligence (AI) estimates (26.0%) (Clymire-Stern et al., 2022). Cover estimates using i-Tree Canopy can be improved by higher number of random points. Nowak (2021) noted that with 1000 random points, the standard error of the cover estimate will be less than 1.6 %.

Our research shows that the potential or available space for tree canopy cover ranged from 30.66% to 51.11% among the 15 Polish study sites. For comparison, Oliveira et al. (2022) calculated with iTree Canopy increase cover by tree in Naples from 29% to 45%. Analysis of "potential" areas using iTree Canopy showed that trees can be planted mainly on other green areas (lawns) (Fig. 1). However, bare ground areas or places covered with concrete also have great potential. This is important because other authors report an increase in impermeable cover and a decrease in tree canopy cover in cities (Nowak and Greenfield, 2020). In historic parts of cities, a significant increase in tree canopy cover may also be the result of unintentional forest emergence resulting from the lack of cultivation activities on plots excluded from use (Heris et al., 2022; Roman et al., 2021). Doick et al. (2020) and Nix et al. (2023) indicate the lack of long-term studies in cities and the need for further monitoring studies of urban canopy cover.

3.2. *Environmental benefits of urban trees area*

3.2.1. *Carbon sequestration potential*

Different methods, such as field methods and remote sensing methods, have been used to estimate above-ground biomass and carbon sequestration potential of urban tree species (Thacker et al., 2023). Klein et al. (2021) using multi-spectral aerial imagery and LiDAR data calculated a total of 52,000 tons of carbon sequestered in trees for New York City's borough Manhattan. In Canada, using the i-TreeEco model, urban forests were found to store approximately 27,297.8 kt C in above and belowground biomass and sequester approximately 1497.7 kt C year-1 (Steenberg et al., 2023). In this study we used i-Tree Canopy to estimate that annually the trees growing in central districts of Polish cities sequestered from 64.94 tons C (238.12 tons CO_2 Equiv.) to 715.49 tons C (2623.45 tons CO_2 Equiv.). The largest increase was recorded in Wrocław, where the prediction of an increase in land cover with tree canopy was 114%. The amount of C that was sequestered increased from 138.5 tons (507.89 tons CO_2 Equiv.) to 297.4 tons (507.89 tons CO_2 Equiv.) per year (Fig. 2). The smallest increase was calculated for Częstochowa, where the prediction of the increase in land cover with tree canopy was 47.8%. The amount of sequestered C increased from 171.49 tons (628.79 tons CO_2 Equiv.) to 253.62 tons (929.94 tons CO_2 Equiv.) per year (Fig. 2). Generally, model predicts that annually the trees growing in central districts of Polish cities have potential for sequester from 115.66 tons C (424.08 tons CO_2 Equiv.) to 1070.00 tons C (3930 tons CO_2 Equiv.). The iTree Canopy model also allows to calculate the amount of C stored in tree biomass. It was noted that actual value was between 1630.91 tons C (5980.01 tons CO_2 Equiv.) and 17,968.58 tons C (65,884.79 tons CO_2 Equiv.). In turn, potential value was between 2904.6 tons C (10,650.2 tons CO_2 Equiv.) and 26,880.00 tons C (98,570 tons CO_2 Equiv.)

The size of the coverage area for carbon sequestration is important. Liu and Li (2012) showed that the urban forests in areas within the third-ring road of Shenyang stored 337,000 t C, with a C sequestration rate of 29,000 tyr^{-1}. The C stored by urban forests equaled to 3.02% of the annual C emissions from fossil fuel combustion, and C sequestration could offset 0.26% of the annual C emissions in Shenyang. Tulek (2022) found vegetation covering 16.03% of the research area at Wageningen, captured by the tree canopy annually 13.490 tons of carbon, and the total carbon stored by the tree canopy is estimated as 338.840 tons. In turn, Ghorbankhani et al. (2022) estimated two urban sites Nahjol-Balaghe and Pardisan parks (approximately 321 ha) located in Tehran metropolis. They found that 69.08 ha (23.43%) covered with trees and shrubs, and the study area was able to sequestrate 775.3 metric

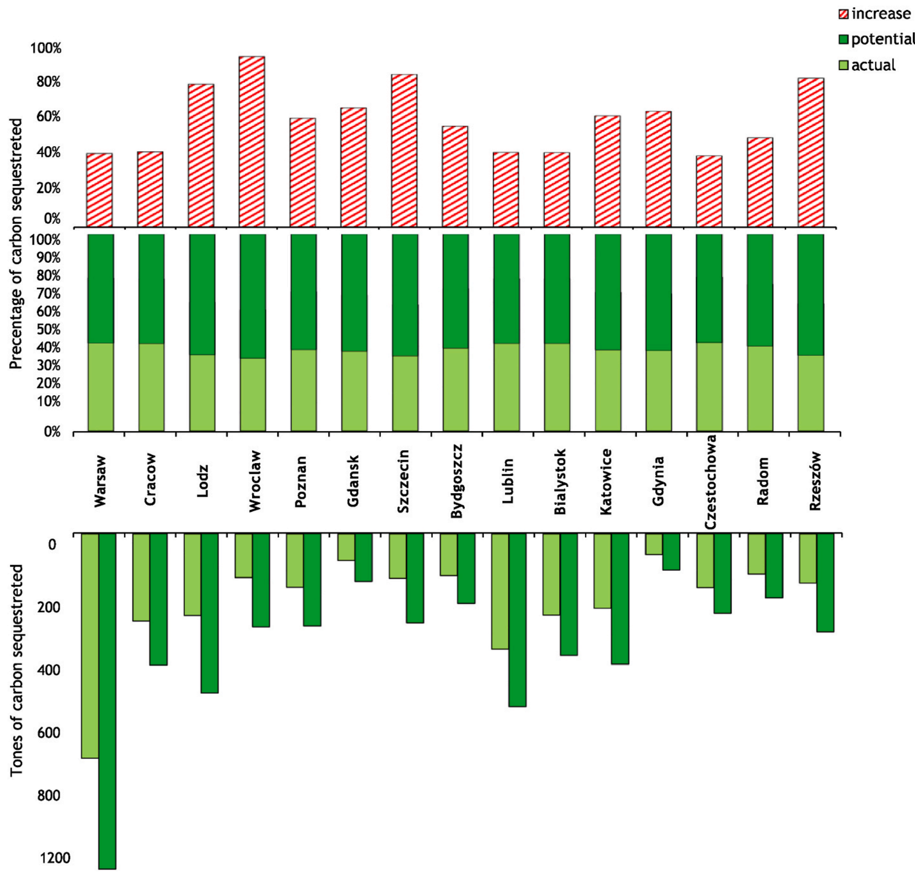

Fig. 2. Annual carbon sequestration by tree communities within studied areas in Polish cities.

tons (m.t) carbon dioxide and to store 19,466.44 m t carbon dioxide in each hectare. Using iTree Canopy, Oliveira et al. (2022) estimated the potential benefits of increasing tree coverage within the boundaries of the Metropolitan City of Naples, Southern Italy. They found that increasing the area covered by tree canopy by 30% increases the value of sequestered carbon by 50% from 112.38 Mtons/year to 169.69 Mtons/year. In spite of the fact that urban afforestation is one of the most promising method for carbon sequestration and storage; Brilli et al. (2022) found that the green areas within the Municipality of Prato can sequester 33.1 ktCO_2 yr^{-1} under actual conditions and 51.0 ktCO_2 yr^{-1} under the afforestation scenario which maximize the CO_2 sequestration capacity; these values compensated only 7.1% and 11% of the total emissions (465.8 ktCO_2 yr^{-1}), respectively.

3.2.2. *Removal of air pollutants NO_2, SO_2, O_3, $PM_{2.5}$, PM_{10}*

Urban forests have been found to be effective in reducing air pollution by mitigating the concentrations of various pollutants such as PM2.5, PM10, NO_2, SO_2, and O_3. However the removal of air pollutants by urban vegetation is influenced by different factors, including ambient pollution concentration, or green coverage and quality (Douglas et al., 2023; Zhai et al., 2022; Miao et al., 2022; Pataki et al., 2021).

The average removal rate of pollution by trees growing on study sites was 0.08–1.98 tonnes/year for PM2.5; 0.21–3.46 tonnes/year for PM10; 0.12–1.81 tonnes for NO_2, 0.04–0.74 tonnes for SO_2, and 0.84–10.93 for O_3 (Fig. 3). The increase in tree canopy coverage was modelled, the ability of the studied areas to absorb pollutants also increased. The increase ranged from 48 to 115%, with an average value of 73%. Hence, potential average removal rate by trees growing on selected areas was calculated as follows: 0,13–2.96 tonnes/year for PM2.5; 0.38–5.19 tonnes/year for PM10; 0.22–2.88 tonnes for NO_2, 0.10–1.10 tonnes for SO_2, and 1.53–16.34 for O_3 (Fig. 3). These findings are consistent with the literature. Wu et al. (2019) using i-Tree Eco model indicated that the PM2.5 removal by urban vegetation in 2015 was 1000.1 tons, and the average removal rate by vegetation was 1.6 g m^{-2} $year^{-1}$. For five future planting scenarios, by increasing vegetation cover by 5% in different elevation zones (<100, 100–300, and >300 m), an annual amount of 1220.6–1308 tones could be achieved (22–31%). Although a similar methodology was used as in our study, the differences are due to a much smaller increase in tree cover. Moreover, i-Tree Eco Model was used for assessment of NO_2 purification by urban forest in Bejing (China). It was found that the average annual absorption in urban areas being significantly lower than in suburban areas. As the reasons population density, building density, forest cover, and the quality of urban forests were noted (Gong et al., 2022). In turn, the model described by McDonald et al. (2007) using FRAME model predicts that after increasing the total tree cover in West Midlands from 3.7% to 16.5%, average primary PM10 concentrations reduced by 10% from 2.3 to 2.1 μg m^{-3} and in consequence removed 110 ton per year of primary PM10 from the atmosphere. If tree cover of the West Midlands increased to a theoretical maximum of 54%, the average PM10 concentration reduced by 26%, removing 200 ton of primary PM10 per year. Similar results obtained for Glasgow, where tree cover increased from 3.6% to 8% and reduced primary PM10 concentrations by 2%, removing 4 ton of primary PM10 per year. If tree cover increases to 21%, primary PM10 air concentrations reduced by 7%, removing 13 ton of primary PM10 per year (McDonald et al., 2007). These results were lower as compared to our. his may be due to the fact that the specifics of the both used models and undoubtedly pose a challenge for further research.

It could be concluded that increasing tree cover leads to significant reductions in primary air pollutants. However, some differences between cities appear. This may be due to both tree species composition, population density as well as geographic location. Use iTree Canopy,

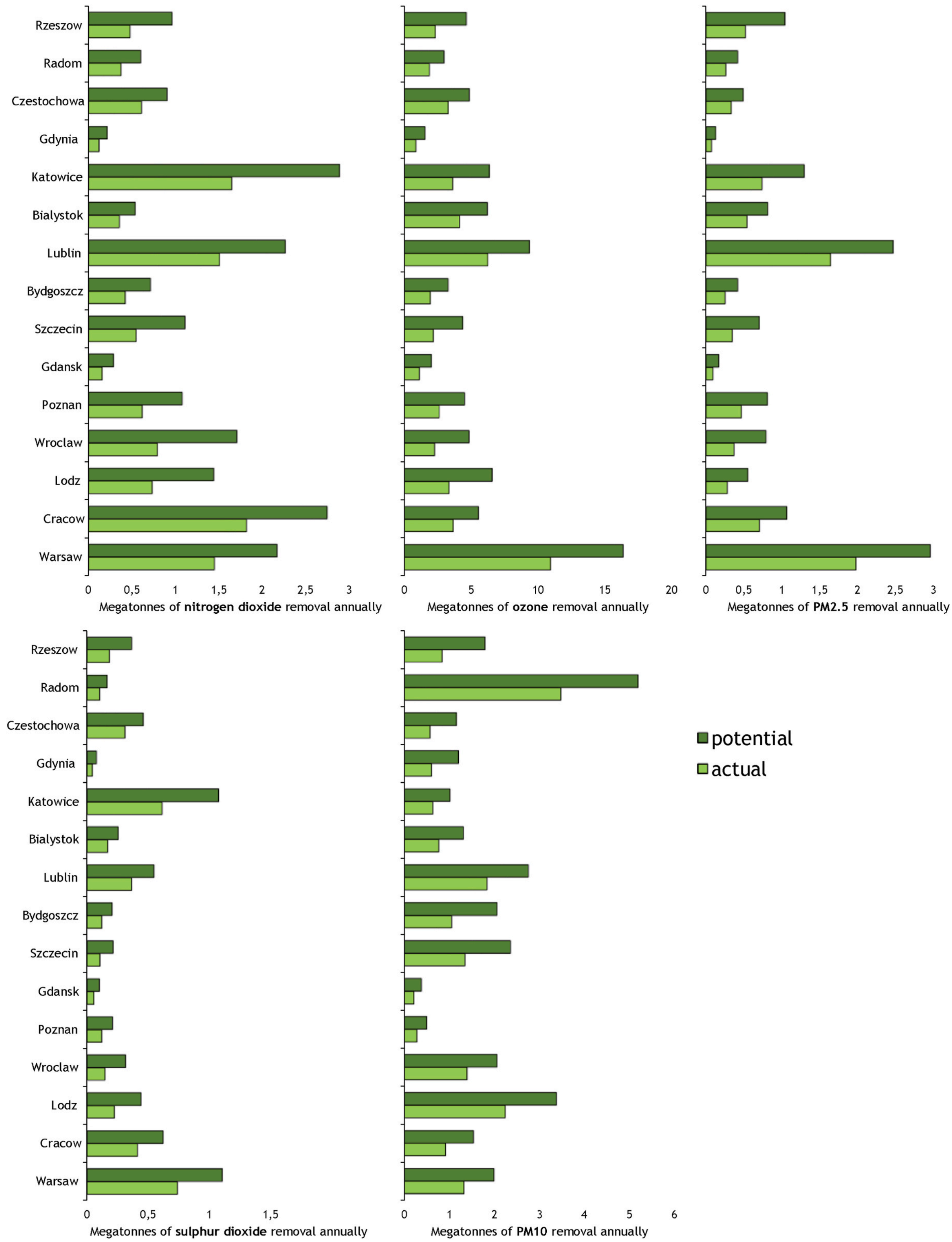

Fig. 3. The air pollution specific tree benefit estimated for studied sites in selected Polish cities by iTree Canopy procedure.

which operate on Google maps online mapping platform shown real potential of every city for air pollution removal. Hence removal capacity of each cities to remove pollution may vary.

3.2.3. Hydrological benefits of trees within urban areas

Urban forests are effective for runoff decrease by intercepting rainfall, delaying runoff, and increasing soil infiltration capacity. Urban trees can retain a sizable volume of annual rainfall in their crowns, delay the flow of stormwater runoff, increase soil infiltration capacity, and provide transpiration of captured runoff for additional stormwater storage (Smets et al., 2019; Marrazzo and Raimondi, 2023; Rahman et al., 2023).

Using i-Tree Canopy it has been estimate the amount of avoided runoff, evaporation, interception, transpiration, potential evaporation, and potential evapotranspiration due to tree cover (Fig. 4). At the selected study sites, on average, these values could increase by 66% due to increase of tree cover. The range of avoided runoff varied from 3139.36 m^3yr^{-1} to 37,542.43 m^3yr^{-1} of water (Fig. 4). In turn, predicted values increased and are within the range of 5592.27 m^3yr^{-1} to 56,153.21 m^3yr^{-1} of water in study site (Fig. 4). For comparison, Babtista et al. (2020) found that doubling the urban canopy cover in the catchment area could reduce annual runoff volume by 30 mm (92 m^3yr^{-1}), indicating that urban forests are effective at reducing runoff. In the case that deciduous trees are planted, the annual runoff reduction would decreased to 24 mm (73 m^3yr^{-1}) and increases to 37 mm (112 m^3yr^{-1}) if only evergreen trees are planted.

The range of evaporation in recent studies compared between actual and potential increased from 19,296.96 to 244,779.87 m^3yr^{-1} to 34,374.42- 366,123.73 m^3yr^{-1} (Fig. 4). This is important, to reduce the harm intensity of the so-called Urban Heat Islands (Paschalis et al., 2021). However management practices such as artificial irrigation and fertilization could affect urban forest evapotranspiration (Lee et al., 2021).

The range of actual transpiration calculated by iTree Canopy model was equal from 31.112.24 m^3yr^{-1} to 217,930.58 m^3yr^{-1} of water (Fig. 4). In turn, predicted values increased and are within range from 56,663.18 m^3yr^{-1} to 328,815.82m^3yr^{-1} of water (Fig. 4). Some authors found that different species of trees have different transpiration rates with some species exhibiting higher rates than others (Chen et al., 2023; Ponte et al., 2021). Wang et al. (2014) observed great differences in the response of whole-tree transpiration (Et) of Chinese pines (*Pinus tabulaeformis*) growing in the center of Beijing, China to environmental factors at different time scales. However, Pataki et al. (2011) hypothesized that species composition would be a more important driver of spatial variability in urban-forest transpiration than meteorological variables. The results of our research cannot directly confirm the hypothesis of Pataki et al. (2011), because the hydrological indicators used in the iTreeCanopy model are average data and do not directly refer to specific tree species. However, the results obtained in the case of carbon sequestration modeling, discussed in section 3.5, clearly indicate that species composition and cover size are important factors in the effectiveness of this process.

3.3. Inventory of urban dendroflora within Polish cities

Street trees, planted in public rights-of-way, contribute significantly to the urban forest, enhancing species composition, biodiversity, and biomass (Anderson et al., 2023). According to the inventory data, 44 taxa of tree species were identified as the most common among the studied Polish cities. The list of taxa whose number exceeded 1% of the total is presented in Fig. 5. Two species are the most numerous - *Acer platanoides* (14.5%) and *Tilia cordata* (11.45%). Additionally, the following species occur in large numbers (between 3 and 6%): *Betula pendula, Quercus robur, Robinia pseudoacacia, Fraxinus excelsior, Acer pseudoplatanus, Aesculus hippocastanum* or *Acer campestre* (Fig. 5). And these are mainly native species. Similar tree species in European urban environments were detected by other authors, such *Platanus* × *hispanica, Celtis australis, Quercus ilex, Salix alba, Quercus rubra, Pinus sylvestris, Tilia tomentosa, Fraxinus excelsior, Acer campestre, Acer platanoides, Malus* spp., and *Quercus robur* (Chi et al., 2021, Caneva et al., 2020; Lind et al., 2023; Petrova and Petkova, 2023; Fauk and Schneider, 2023). However, this is not the rule throughout Europe. According to Kalusova et al. (2017) in Italy 277 urban street trees species were identified, of which approximately 60% were exotic.

Similar like in our study, also other authors showed that usually only few species were dominant in urban space. Tilia × europaea was one of the most widely planted urban tree species in Northwest Europe, with historical plantings showing higher genetic diversity compared to current commercial planting stocks (Vanden Broeck et al., 2018). This relationship is also observed in other countries around the world. In Indonesian urban forests, the predominant tree species were *Pterocarpus indicus, Delonix regia, Polyalthia longifolia, Lagerstroemia speciosa, Mimusops elengi, Samanea saman, Tectona grandis, Ficus benjamina, Mangifera indica,* and *Tamarindus indica* (Fitria et al., 2022). In Banda Aceh, Indonesia, the most commonly found tree species in the urban forest was Cemara laut (*Casuarina equisetifolia*) (Yanti et al., 2023). In the largest US cities, the composition of tree species in urban forests varies, with native trees comprising 0.44%–85.6% of the tree populations (McCoy et al., 2022). In four urban forests were primarily dominated *Fraxinus mandshurica, Quercus mongolica, Pinus sylvestris* var. *mongolica*, and *Pinus tabulaeformis* var. *mukdensis* (Ao et al., 2022).

Nowdays, it is noted potential for using exotic (such Chineese) tree species in European urban areas, particularly in regions with expected drier and hotter conditions (Broek et al., 2018). In our research, we noticed the numerous occurrences of black locust. This species, native to North America, is now considered problematic in Europe. Despite its high resistance to drought, it is very expansive and strongly transforms the soil and limits the species diversity of soil organisms (Vítková et al., 2017). The presence of such tree species is another problem emerging in cities with climate change.

3.4. The similarity of tree communities growing under Polish conditions

Planting urban trees species are usually selected based on their suitability for local climatic conditions, aesthetic appeal, dimension, and ability to adapt to the urban environment (Shotaroska et al., 2019). Hence, climate, geographic distance, and human decisions play a role in shaping the variation in tree community composition among cities (Divakara et al., 2022, Frigerio et al., 2023, Petrova and Petkova (2023). Our research confirmed that the communities of trees growing in cities with similar climatic conditions or located close to each other are the most similar, demonstrating that these tree communities adapted to local conditions (Fig. 6).

Additionally, urban forests have become more homogeneous worldwide, resulting in minimal scale dependence in compositional similarity (McCoy et al., 2022). Native species are typically better suited to local conditions, however, some non-native species can also be beneficial if they are non-invasive and well-suited to urban environments. Introduced species significantly homogenize tree communities across cities (Jenerette et al., 2016). It could be concluded that similarity of urban forests declines as the spatial scale increases, regardless of whether native or non-native species are considered (Yang et al., 2015), due to dependence that larger areas have greater diversity.

3.5. The effect of tree species composition on carbon storage in urban areas

The ecological effect we focused on was the estimation of the number of trees and the time necessary to store carbon, in the amount determined during the analyzes in section 3.2.3. Carbon sequestration potential and shown in Fig. 2. The tree species composition in an urban area has a significant impact on the amount of carbon stored. By increasing the number of trees and promoting species diversity, urban areas can enhance their carbon sequestration capacity and contribute to climate change mitigation. Studies in Banda Aceh City and Guiyang City highlighted that higher tree density resulted in greater above-ground biomass, carbon stock, and carbon sequestration values in urban forests (Zhou et al., 2022). We adopted two scenarios using differing species compositions. In the first scenario, the 20 most common tree species in a given city were applied to the analysis ("city specific option"). The current species composition was used and thus the percent of each species present in the community was maintained. In the second scenario, the top 20 tree species that commonly grow in Polish cities were applied to all communities ("standard option"). Thus, it was assumed that the share of individual species in each community would be the same. In the first stage, the model compared how many trees needed to

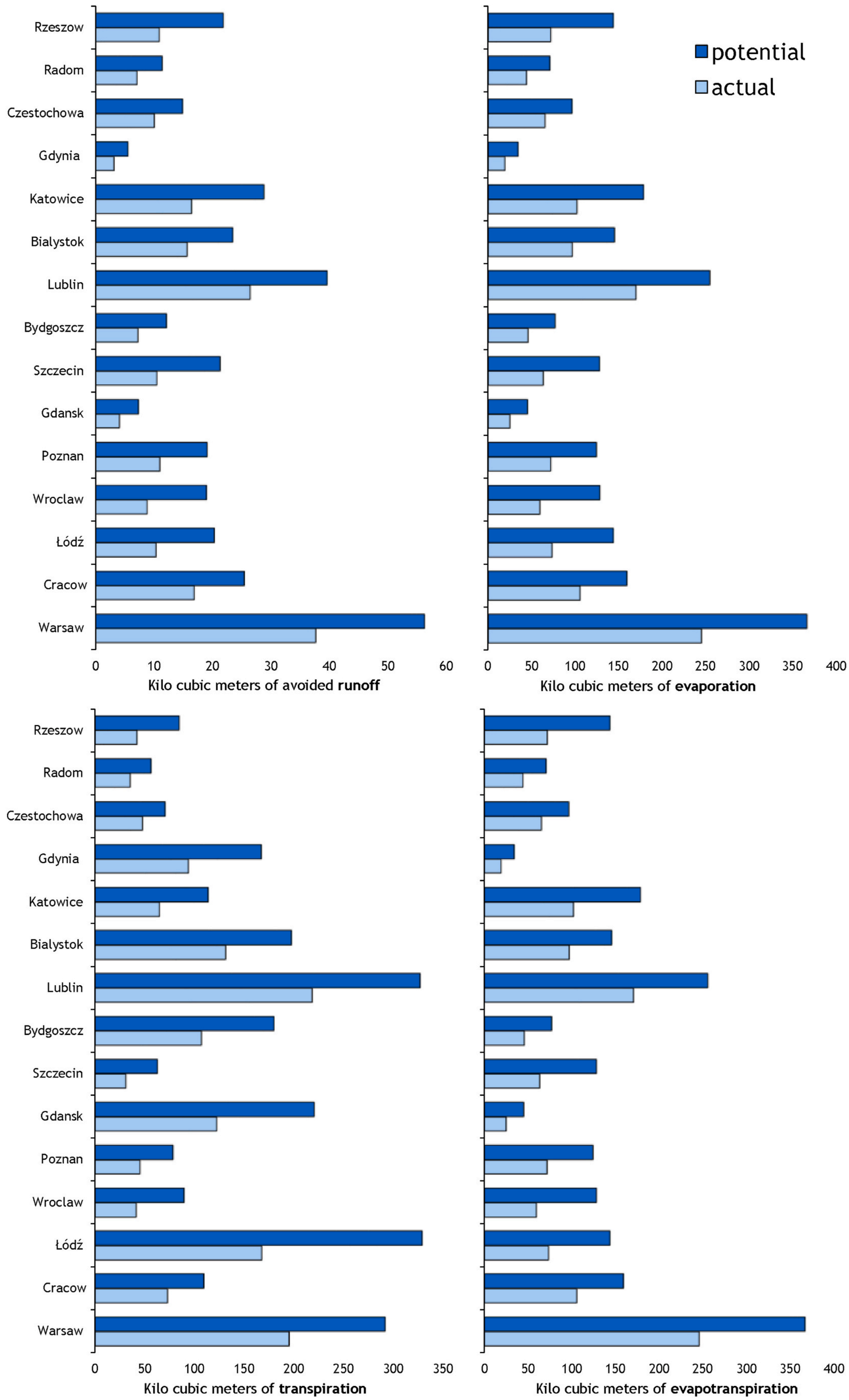

Fig. 4. Hydrological benefits in studied areas within Polish cities estimated by iTree Canopy procedure.

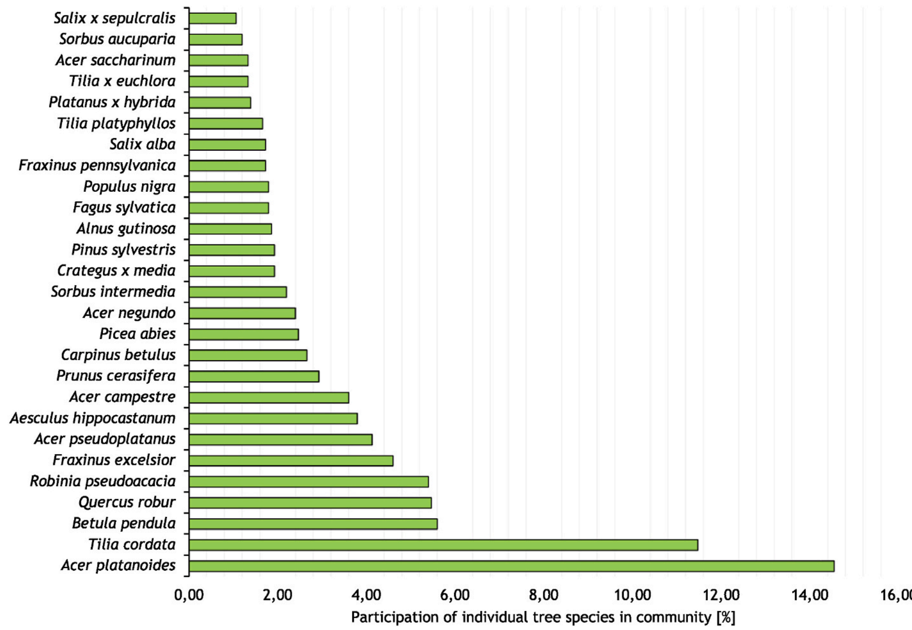

Fig. 5. The most common tree species occurring in Polish cities.

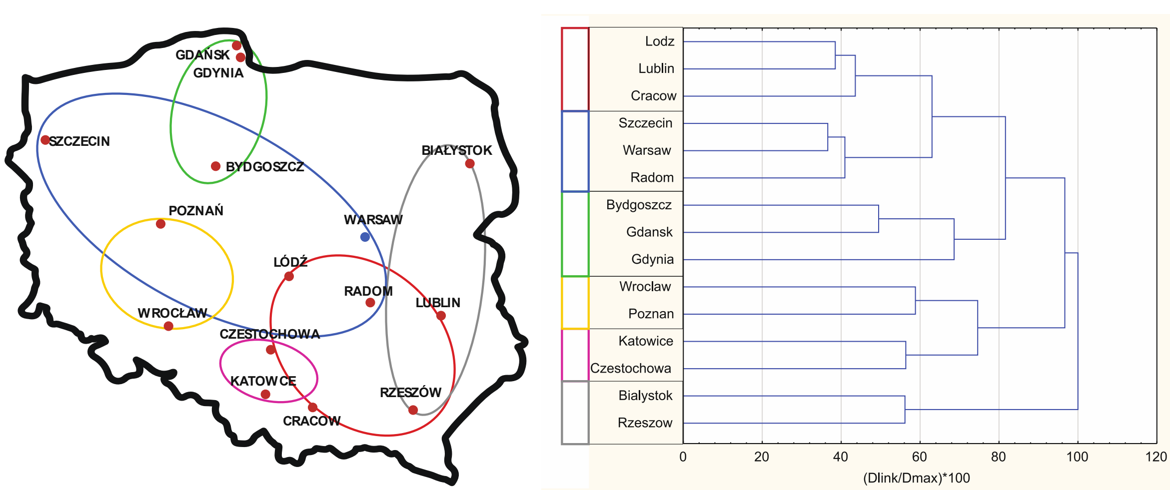

Fig. 6. The mutual estimation of similarity of tree communities growing in studied Polish cities with use Ward's Hierarchical Clustering Method. The different colours mark cities whose tree communities are similar (the value Dlink/Dmax should not exceed 0.6). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

be planted to achieve the amount of carbon stored determined for each area as a function of time, using each of the two scenarios described above (Table 3). It was found that to achieve the desired effect in the first year after planting, it would be necessary to plant from 23,005 to 164, 860 4 cm DBH seedlings. Taking 55 years as the cut-off age, it was calculated that the smallest number of trees necessary to achieve the desired carbon storage was 37 trees in Gdynia, and the largest number was 305 trees in Warsaw. These results were impacted by the available plantable space in the studied area. However, when comparing the two scenarios, it was noticed that this effect was achieved faster in the case of tree communities characteristic of a given place ("city specific option"). The difference between scenarios I and II expressed as a percentage was the highest in the case of Warsaw (the largest area) and amounted to 38%. However, in the first year, the number of necessary trees was lower for scenario II (standard option). Other studies have shown that tree density is a key factor in determining aboveground carbon storage in urban woody vegetation (Devi et al., 2021, Lee et al., 2023). Wei et al. (2023) found that following combination of factors was the most conducive to aboveground carbon storage: a tree density of 2200 trees/ha, canopy cover of 50%, species diversity of 1.2, and species evenness of 0.8 in the transect.

The next stage of this work compared the number of trees necessary to achieve the ecological effect/carbon storage goal over a 100-year period if Warsaw was taken as the reference city, where the increase in carbon sequestration was the highest among studied areas and was 354,510 kg/year. It was found that only in 4 cases (Cracow, Gdynia, Radom and Rzeszow) the necessary number of trees was lower than 100 and only in the case of the "cite specific community" scenario (Table 4). In the case of Cracow, Radom and Rzeszów, only a few species dominated the communities. These were *Acer platanoides, Fraxinus excelsior, Tilia cordata* (Cracow); *Acer platanoides, Tilia cordata, Betula pendula, Alnus glutinosa* (Radom) and *Salix alba, Betula pendula, Juglans regia* (Rzeszow). In the contrary, in the case of Gdynia, there was no such dominant group of species in the community. It was identified several species such *Robinia peudoaccacia, Tilia cordata, Tilia platyphyllos, Tilia x europea, Crategus x media, Sorbus intermedia, Acer platanoides, Acer*

Table 3
The number of trees necessary to obtain increase carbon sequestration, specific for every studied area within 0–55 years after planting.

city	increase of carbon sequestration [kg/year]	increase of tree cover area [ha]	number of additional points	city specific (SCO) or standard (SO) option	necessary number of trees to be planting for benefit obtain after:							
					0	10	20	30	33	40	50	55
					years							
Warsaw	354,510	116.00	221	**SCO**	**164,860**	**6448**	**1752**	**765**	**627**	**419**	**266**	**221**
				SO	**160,795**	**8081**	**2209**	**984**	**817**	**562**	**366**	**305**
				difference [%]	*98*	*125*	*126*	*129*	*130*	*134*	*137*	*138*
Cracow	140,790	46.20	177	**SCO**	**65,439**	**2970**	**711**	**314**	**259**	**174**	**112**	**93**
				SO	**63,858**	**3182**	**869**	**387**	**321**	**221**	**144**	**120**
				difference [%]	*98*	*107*	*122*	*123*	*124*	*127*	*129*	*129*
Lodz	249,390	81.50	258	**SCO**	**119,583**	**6054**	**1718**	**762**	**626**	**421**	**265**	**219**
				SO	**113,115**	**7065**	**2004**	**892**	**739**	**508**	**329**	**274**
				difference [%]	*95*	*117*	*117*	*117*	*118*	*121*	*124*	*125*
Wroclaw	159,220	52.00	247	**SCO**	**57,779**	**2843**	**793**	**351**	**289**	**195**	**148**	**103**
				SO	**69,694**	**3568**	**973**	**433**	**360**	**248**	**161**	**134**
				difference [%]	*121*	*126*	*123*	*124*	*125*	*127*	*109*	*130*
Poznan	124,940	40.80	221	**SCO**	**60,480**	**2511.5**	**683**	**297**	**244**	**163**	**104**	**88**
				SO	**56,669**	**2851**	**780**	**347**	**288**	**199**	**129**	**108**
				difference [%]	*94*	*114*	*114*	*117*	*118*	*122*	*124*	*122*
Gdansk	67,940	22.20	213	**SCO**	**29,700**	**1501**	**420**	**187**	**155**	**105**	**69**	**57**
				SO	**30,815**	**1684**	**466**	**209**	**178**	**121**	**78**	**64**
				difference [%]	*104*	*112*	*111*	*112*	*115*	*115*	*114*	*111*
Szczecin	144,390	47.20	238	**SCO**	**66,580**	**2856**	**770**	**336**	**275**	**184**	**117**	**96**
				SO	**64,398**	**3215**	**882**	**393**	**326**	**225**	**146**	**120**
				difference [%]	*97*	*113*	*115*	*117*	*118*	*122*	*125*	*126*
Bydgoszcz	90,100	29.50	235	**SCO**	**44,661**	**2404**	**677**	**298**	**245**	**166**	**105**	**88**
				SO	**40,867**	**2552**	**724**	**322**	**267**	**183**	**119**	**99**
				difference [%]	*92*	*106*	*107*	*108*	*109*	*111*	*113*	*113*
Lublin	184,260	60.00	256	**SCO**	**94,993**	**4754.07**	**1318**	**580**	**478**	**324**	**207**	**172**
				SO	**83,575**	**5270**	**1497**	**667**	**567**	**387**	**248**	**206**
				difference [%]	*88*	*111*	*114*	*115*	*119*	*119*	*120*	*120*
Bialystok	129,510	42.60	216	**SCO**	**51,301**	**4286**	**1294**	**580**	**478**	**322**	**204**	**167**
				SO	**58,742**	**4758**	**1426**	**640**	**528**	**361**	**234**	**194**
				difference [%]	*114.5*	*111.0*	*110.2*	*110.4*	*110.6*	*112.0*	*114.8*	*116.6*
Katowice	178,030	58.50	224	**SCO**	**70,176**	**3588**	**1010**	**460**	**383**	**265**	**178**	**153**
				SO	**80,749**	**4024**	**1098**	**489**	**406**	**280**	**182**	**152**
				difference [%]	*115.1*	*112.2*	*108.7*	*106.3*	*106.0*	*105.4*	*102.1*	*99.4*
Gdynia	50,720	16.61	247	**SCO**	**31,535**	**1180**	**311**	**133**	**109**	**72**	**46**	**37**
				SO	**23,005**	**1166**	**323**	**142**	**119**	**82**	**53**	**44**
				difference [%]	*73.0*	*98.8*	*104.1*	*106.7*	*109.6*	*113.1*	*115.3*	*118.9*
Czestochowa	82,130	26.84	190	**SCO**	**38,940**	**1813**	**499**	**220**	**182**	**124**	**82**	**70**
				SO	**37,252**	**1856**	**507**	**226**	**192**	**131**	**84**	**70**
				difference [%]	*95.7*	*102.4*	*101.5*	*102.6*	*105.3*	*105.2*	*102.3*	*99.4*
Radom	76,710	25.10	231	**SCO**	**34,967**	**1464**	**394**	**172**	**141**	**95**	**61**	**52**
				SO	**34,793**	**39,750**	**478**	**213**	**177**	**122**	**79**	**66**
				difference [%]	*99.5*	*2715.2*	*121.3*	*123.8*	*125.1*	*128.0*	*129.2*	*127.5*
Rzeszow	90,100	29.45	235	**SCO**	**35,804**	**1626**	**436**	**189**	**153**	**103**	**64**	**52**
				SO	**34,793**	**1690**	**459**	**205**	**171**	**118**	**76**	**63**
				difference [%]	*97.2*	*103.9*	*105.3*	*108.5*	*111.7*	*114.7*	*118.9*	*121.3*

pseudoplatanus, Aesculus hippocastanum, Salix alba, Fagus sylvatica, Betulus pendula, Fraxinus excelsior.

In the last stage of our research, the area with the lowest potential for carbon sequestration - 50,720 kg C/year (Gdynia) was used as a reference area. Also in this analysis, 100 trees were assumed as the number necessary to achieve the ecological effect. It was found that it would take 30–50 years for tree communities to sequester carbon at this level. This effect was recorded the fastest for Warsaw - 30 years, and the longest for Białystok - 45 years (Table 5). This was related to both the species composition and climatic conditions of each community. The carbon sequestration capacity tends to decrease gradually with changes in forest structure and is positively correlated with diameter at breast height (DBH), community density, biomass and hierarchical structure.

Havu et al. (2022) found that the Alnus trees were able to reach the compensation point when street tree plantings turned from an annual source into a sink – after 12 years, while this point was reached by Tilia trees after 14 years. However, these moments naturally vary from site to site depending on the growing media, planting density, tree species, and climate. Another study showed that in a peri-urban degraded plantation, the more intense thinning resulted in a positive impact on carbon sequestration, with a payback time of about 7 years for recovering the harvested volume (Chiavetta et al., 2023). In turn, the Lind et al. (2023) found the link between the time by which compensation of initial carbon emissions was achieved and growth rate of the different species. This research carried out in Umeå (Sweden) selected Salix alba, Quercus rubra and Pinus sylvestris due to significant differences in their growth rates. The results showed that within 16 years of planting, trees compensated initial carbon emissions, especially the fast-growing Salix alba, so lees than in our research. Moreover, the study Orlandi et al. (2022) confirmed role of specific site conditions for carbon store by urban trees. The similar results have been reported on other continents (Al-Nadabi and Sulaiman, 2023; Snehlata et al., 2021).

4. Conclusion

Selection of tree species in urban areas considers ecological roles, social-economic functions, and thriving in anthropogenic environments. Planting trees in European cities helps climate change, reduces energy flow to surfaces, lowers temperatures, and improves ecological functions. Increasing tree cover in cities enhances carbon sink capabilities, contributing to urban sustainability and environmental health. Tree canopy cover in urban areas varies over time due to management

Table 4
The number of trees necessary to obtain increase carbon sequestration, for maximal calculated carbon storage within 0–100 years after planting (reference city Warsaw).

City	city specific (SCO) or standard (SO) option	necessary number of trees to be planting for benefit obtain after										
		0	10	20	30	40	50	60	70	80	90	100
		years										
Cracow	SCO	164,775	7479	1790	790	439	281	198	152	125	108	98
	SO	160,795	8012	2187	974	557	363	255	194	157	135	121
	difference [%]	*98*	*107*	*122*	*123*	*127*	*129*	*129*	*128*	*126*	*125*	*124*
Lodz	SCO	169,988	8606	2442	1083	599	377	262	195	156	131	116
	SO	152,755	10,043	2849	1268	722	468	330	245	194	161	140
	difference [%]	*90*	*117*	*117*	*117*	*121*	*124*	*126*	*126*	*124*	*122*	*120*
Wroclaw	SCO	128,647	6330	1766	781	433	323	190	146	121	106	96
	SO	155,176	7944	2165	965	551	359	248	187	150	128	114
	difference [%]	*121*	*125*	*123*	*124*	*127*	*111*	*131*	*128*	*124*	*121*	*119*
Poznan	SCO	171,620	7126.1	1937	844	461	296	274	168	139	122	111
	SO	160,795	8091	2212	985	563	367	258	195	158	136	122
	difference [%]	*94*	*114*	*114*	*117*	*122*	*124*	*94*	*116*	*114*	*111*	*109*
Gdansk	SCO	154,975	7830	2193	975	550	357	231	177	144	125	112
	SO	160,795	8790	2433	1089	634	408	264	199	160	136	121
	difference [%]	*104*	*112*	*111*	*112*	*115*	*114*	*114*	*113*	*111*	*109*	*108*
Szczecin	SCO	163,468	7011	1891	824	452	287	196	150	123	106	95
	SO	158,112	7944	2165	965	551	359	253	192	156	135	121
	difference [%]	*97*	*113*	*115*	*117*	*122*	*125*	*129*	*128*	*127*	*127*	*127*
Bydgoszcz	SCO	175,723	9458	2663	1173	652	415	292	216	171	141	123
	SO	160,795	10,043	2849	1268	722	468	349	258	204	168	145
	difference [%]	*92*	*106*	*107*	*108*	*111*	*113*	*119*	*120*	*119*	*119*	*118*
Lublin	SCO	182,762	9146	2535	1116	623	398	279	208	165	138	121
	SO	160,795	10,139	2881	1283	744	477	334	248	196	162	141
	difference [%]	*88*	*111*	*114*	*115*	*119*	*120*	*119*	*119*	*118*	*117*	*116*
Bialystok	SCO	140,428	11,733	3542	1587	881	556	382	281	216	173	145
	SO	160,795	13,025	3903	1752	988	640	450	334	259	209	175
	difference [%]	*115*	*111*	*110*	*110*	*112*	*115*	*118*	*119*	*120*	*121*	*120*
Katowice	SCO	139,741	7144	2012	917	528	355	265	211	177	155	141
	SO	160,795	8012	2187	974	557	363	255	194	157	135	121
	difference [%]	*115*	*112*	*109*	*106*	*105*	*102*	*96*	*92*	*89*	*87*	*86*
Gdynia	SCO	220,418	8245	2171	931	506	321	215	160	128	111	98
	SO	160,795	8152	2261	993	572	370	260	197	159	137	121
	difference [%]	*73*	*99*	*104*	*107*	*113*	*115*	*121*	*123*	*124*	*124*	*123*
Czestochowa	SCO	168,083	7827	2154	950	536	354	262	208	174	153	138
	SO	160,795	8012	2187	974	564	363	255	194	157	135	121
	difference [%]	*96*	*102*	*102*	*103*	*105*	*102*	*97*	*93*	*90*	*89*	*88*
Radom	SCO	161,597	6766	1822	794	440	207	160	133	117	106	111
	SO	154,494.9	8081	2209	984	562	367	262	197	158	135	120
	difference [%]	*96*	*119*	*121*	*124*	*128*	*177*	*163*	*149*	*136*	*128*	*108*
Rzeszow	SCO	152,708	7649	2164	965	539	348	199	146	119	106	98
	SO	160,795	7808	2123	946	547	352	287	189	154	133	120
	difference [%]	*105*	*102*	*98*	*98*	*102*	*101*	*144*	*129*	*129*	*125*	*122*
for maximal calculated carbon storage - 354,510 kg C/year (on the base of Warsaw)												

practices, historical processes, and local policies. Analysis using iTree-Canopy shows limited potential to increase tree canopy coverage in historic city districts, with 30–40% in Polish cities. Limited plantable space in urban areas affects achieving desired effects like increased tree density. The program allows precise determination of tree canopy coverage in studied areas. Expansion of tree planting areas often occurs in other green spaces, particularly lawns.

The challenge is to introduce tree species that can adapt to harsh city conditions. Urban trees face difficulties in degraded environments, impacting growth and ecosystem services. Urban forests must serve specific environmental functions for a long time, so selecting suitable species is crucial for decades. Structural changes in public spaces, like adding green infrastructure, are slow due to urban development and limited tree space. *Tilia cordata* and *Acer platanoides* are the dominant species in Polish cities.

Urban forests are important for managing stormwater, improving air quality, and enhancing city resilience to climate change. The iTree algorithms demonstrate that tree communities tailored to their environment can sequester more carbon. Species adapt to habitat and climate, affecting carbon storage potential. It takes around 50 years to increase carbon storage significantly.

Urban trees carbon sequestration varies due to factors like environment, tree age, and pests; using an average value may not be suitable for all cities. Urban conditions differ from natural ecosystems, making it challenging for forest-based models to accurately estimate carbon sequestration potential in cities. iTree models may not capture urban greening species' specifics, leading to difficulties in measuring carbon stocks in urban forests. iTree may not consider urban environments' dynamic nature and changing climate, affecting its accuracy in predicting long-term carbon sequestration trends. Advanced modeling tools are needed to improve carbon sequestration estimations in urban forests.

Climate change threatens urban trees by increasing mortality risk due to heatwaves, lack of rain, and extreme weather. Habitat changes can impact biodiversity and shift species dominance in urban tree communities. Climate change may lead to the replacement of temperate species like linden with those better suited to higher temperatures. Identifying vulnerable species, implementing planting protocols, and long-term monitoring are crucial for urban tree population sustainability amidst climate change.

Concerning on main directions of strategies for old city districts it should be mentioned that introducing a specific range of tree species could increase ecological benefits and resilience of urban forest in old city districts. Increasing the number of trees and promoting species

Table 5
The number of trees necessary to obtain increase carbon sequestration, for maximal calculated carbon storage within 0–50 years after planting (reference city Gdynia).

city	city specific (SCO) or standard (SO) option	necessary number of trees to be planting for benefit obtain after:					
		0	10	20	30	40	50
		years					
Warsaw	**SCO**	**23,587**	**922**	**251**	**109**	**60**	**38**
	SO	**23,005**	**1156**	**316**	**141**	**80**	**52**
	diferrence [%]	*98*	*125*	*126*	*129*	*134*	*138*
Cracow	**SCO**	**23,575**	**1070**	**256**	**113**	**63**	**40**
	SO	**23,005**	**1146**	**313**	**139**	**80**	**52**
	diferrence [%]	*98*	*107*	*122*	*123*	*127*	*129*
Lodz	**SCO**	**24,320**	**1231.28**	**349**	**155**	**86**	**54**
	SO	**23,005**	**1437**	**408**	**181**	**103**	**67**
	diferrence [%]	*95*	*117*	*117*	*117*	*121*	*124*
Wroclaw	**SCO**	**18,406**	**906**	**253**	**112**	**62**	**48**
	SO	**22,201**	**1137**	**310**	**138**	**79**	**51**
	diferrence [%]	*121*	*125*	*123*	*124*	*127*	*108*
Poznan	**SCO**	**24,550**	**1020**	**277**	**121**	**66**	**42**
	SO	**23,005**	**1158**	**316**	**141**	**81**	**52**
	diferrence [%]	*94*	*114*	*114*	*117*	*122*	*124*
Gdansk	**SCO**	**22,172**	**1120**	**314**	**139**	**79**	**51**
	SO	**23,005**	**1258**	**348**	**156**	**91**	**58**
	diferrence [%]	*104*	*112*	*111*	*112*	*115*	*114*
Szczecin	**SCO**	**23,388**	**1003**	**270**	**118**	**65**	**41**
	SO	**22,621**	**1137**	**310**	**138**	**79**	**51**
	diferrence [%]	*97*	*113*	*115*	*117*	*122*	*125*
Bydgoszcz	**SCO**	**25,141**	**1353**	**381**	**168**	**93**	**59**
	SO	**23,005**	**1437**	**408**	**181**	**103**	**67**
	diferrence [%]	*92*	*106*	*107*	*108*	*111*	*114*
Lublin	**SCO**	**26,148**	**1309**	**363**	**160**	**89**	**57**
	SO	**23,005**	**1451**	**412**	**184**	**107**	**68**
	diferrence [%]	*88*	*111*	*114*	*115*	*119*	*120*
Bialystok	**SCO**	**20,091**	**1679**	**507**	**227**	**126**	**80**
	SO	**23,005**	**1864**	**558**	**251**	**141**	**92**
	diferrence [%]	*115*	*111*	*110*	*110*	*112*	*115*
Katowice	**SCO**	**19,993**	**1022**	**288**	**131**	**76**	**51**
	SO	**23,005**	**1146**	**313**	**139**	**80**	**52**
	diferrence [%]	*115*	*112*	*109*	*106*	*105*	*102*
Czestochowa	**SCO**	**24,048**	**1120**	**308**	**136**	**77**	**51**
	SO	**23,005**	**1146**	**313**	**139**	**81**	**52**
	diferrence [%]	*96*	*102*	*102*	*103*	*105*	*102*
Radom	**SCO**	**23,120**	**968**	**261**	**114**	**63**	**41**
	SO	**23,005**	**1156**	**316**	**141**	**80**	**52**
	diferrence [%]	*100*	*119*	*121*	*124*	*128*	*129*
Rzeszow	**SCO**	**21,848**	**1120**	**314**	**139**	**79**	**51**
	SO	**23,005**	**1117**	**304**	**135**	**78**	**50**
	diferrence [%]	*105*	*100*	*97*	*97*	*100*	*98*

for minimal calculated carbon storage - 50,720 kg C/year (on the base of Gdynia)

diversity can enhance carbon sequestration capacity in urban areas.

Finally, we identified several future research directions.

- conducting long-term assessments to understand the sustained environmental benefits provided by urban trees over time;
- investigating the resilience of urban tree species to climate change effects and exploring strategies to enhance their adaptability in urban environments;
- quantify the ecosystem services provided by urban trees, considering factors like tree size, health, and species composition to better understand their overall environmental impact;
- community engagement and education programs to raise awareness about the environmental benefits of urban trees, fostering a culture of urban forest conservation and management
- consider the influence of elevated CO_2 concentration on tree carbon sequestration, in long period.

CRediT authorship contribution statement

Małgorzata J. Kacprzak: Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Alexis Ellis:** Writing – original draft, Validation, Software, Methodology. **Krzysztof Fijałkowski:** Writing – original draft, Software, Data curation. **Iwona Kupich:** Writing – original draft, Software, Data curation. **Piotr Gryszpanowicz:** Validation, Resources, Data curation. **Eric Greenfield:** Writing – original draft, Validation, Methodology, Data curation. **David Nowak:** Validation, Methodology.

Declaration of competing interest

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Data availability

Data will be made available on request.

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