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(Un)just Distribution of Visible Green Spaces? A Socio-Economic Window View Analysis on Residential Buildings: The City of Cologne as Case Study

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Abstract
As urbanization processes, climate disasters such as heat waves, or pandemics such as COVID-19, increase, prioritizing visible green space is crucial to provide equitable access to green spaces for vulnerable groups with limited mobility. In the long term, this will enable sustainable and resilient urban development. In this study, we examined green window views in residential buildings to identify patterns of distributive equity for seniors and children, considering their socioeconomic status for the first time. We combined the methodology around the BGWVI and the methodological framework by Huang et al. (*Urban Forestry & Urban Greening* 95: 128,313:1–128,313:12, 2024) to measure the visibility potential of green spaces for approximately 160,000 residential buildings in order to geostatistically analyze the equity of the spatial distribution of visible urban green spaces. Using the Gini coefficient, the share index, and the location entropy, an evaluation of the access to visible green spaces according to socio-economic status and age group was carried out at the district level for the City of Cologne, Germany. The results show that children and the elderly have slightly higher percentages of visible green space than the social mean percentage. In addition, the influence of the mean net household income on visual green spaces is low. These findings underscore the importance of visibility as an access alternative in urban green space planning for an equitable and resilient urban environment.

Keywords Urban green spaces · Visibility analysis · BGWVI · Urban structure types · Open source and open data · Socio-ecological justice

Introduction

Urban green spaces provide a range of ecosystem services to urban residents. As demonstrated by Esperon-Rodriguez et al. (2020), Semeraro et al. (2021), and Wang et al. (2022), the provision of food, improvement of air quality, regulation of urban water and microclimate, as well as prevention of erosion are some of the key ecosystem services provided by green spaces. Moreover, accessible green spaces offer city dwellers a range of socio-cultural benefits, including enhanced urban esthetics, opportunities for relaxation and recreation, incentives for creative and artistic pursuits, and the promotion of spiritual experiences. The variety of these effects is contingent upon the spatial characteristics, location, and ecological features of green spaces. One of the principal objectives of green space planning is to facilitate sustainable and resilient urban development, as outlined in Sustainable Development Goals (SDGs) 11.3 and 11.7, as well as the Sendai Framework (UNISDR 2017; United Nations 2017). The provision, maintenance, and creation of fairly available and accessible green spaces play a pivotal role in the implementation of these goals. A plethora of guidelines for planning practice define and anchor these types of access in green space planning, thus serving as a foundational point of reference for research endeavors

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(Blum et al. 2023; Gälzer 2001, pp. 61–68; Richter 1981, pp. 73–76).

In addition to existing physical limitations, climate disasters, such as heatwaves or pandemics such as the 2019 novel coronavirus disease (COVID-19), place a particular burden on vulnerable groups, restricting their necessary access to urban green spaces. The resulting changes in access potential highlight the need to integrate and promote visibility as an access alternative in green space planning in residential environments (Amerio et al. 2020; Basu et al. 2024; Pijpers and van Melik 2020). Prior research has demonstrated a multitude of significant effects of visible green space. In particular, the presence of visible green spaces in residential environments causes changes in auditory perception, cognition, economic use of real estate, health, and mobility behavior, as shown in Fig. 1 (Amerio et al. 2020; Bishop et al. 2004; Hartig et al. 2003; Hui and Liang 2016; Hull et al. 1996; Kley and Dovbishchuk 2021; Olszewska-Guizzo et al. 2018; Sun et al. 2018; Ugolini et al. 2021). The beneficial impact observed in the population can be attributed to the concept of biophilia, which argues that humans possess an intrinsic affinity for nature, other life forms, habitats, and ecosystems (Fromm 1973; Wilson 1984; Kalla et al. 2024).

It is thus necessary to ensure that all members of society have equal access to green spaces, including visibility, in order to foster the development of sustainable and resilient urban areas. This is particularly important for vulnerable populations, who may be more affected by environmental factors. The field of environmental justice encompasses four core components (Martin et al. 2016; Schlosberg 2007; Schröder-Bäck 2012): spatial distributional equity, recognition, participation, and capabilities. Distributional equity pertains to the necessity of ensuring that all individuals have equal access to environmental resources and amenities (G. Bolte et al. 2012, pp. 15–37; Schlosberg 2007). This principle constitutes a pivotal tenet within the domain of socio-political movements advocating for environmental justice. In accordance to United Nations (2015), Robinson et al. (2022) as well as Huang et al. (2024), this study employs the term "socio-ecological equity," which posits that the distribution and access to green spaces should be equitable and fair for all urban residents, irrespective of their financial status, gender, or age.

Research on the distributive equity of green spaces has previously focused on aspects of availability and accessibility, both globally and locally (Anguelovski et al. 2022; Triguero-Mas et al. 2022; Weigand et al. 2023). Visibility analyses, with a particular focus on equity, have primarily examined visible green spaces from the perspective of the street (Dong et al. 2018; Huang et al. 2024; Lu 2019). Kley and Dovbishchuk (2024) conducted the first comprehensive examination of window views using a population survey and explored the impact of visual green space access on subjective well-being, accounting the influence of observers' socio-economic status. Our study builds on the aforementioned research on green window views in residential areas. The objective of this study is the assessment of green window views to identify patterns of distributive justice for seniors and children at a broad level for the first time, with detailed differentiation by city district and urban structure type. Therefore, our contributions in the following article are:

Firstly, we measure the spatial distribution of green window views for buildings with residential purpose of various urban structure types in the City of Cologne, Germany, using the Building Green Window View Index (BGWVI) to secondly enable an investigation of the equitable distribution of visible green spaces at city district level using the geostatistical framework by Huang et al. (2024). Thirdly, we analyze the availability of green window views in relation to the age and socio-economic status of Cologne's population.

The BGWVI enables scalable visibility analysis at the building level, which generates information on visibility

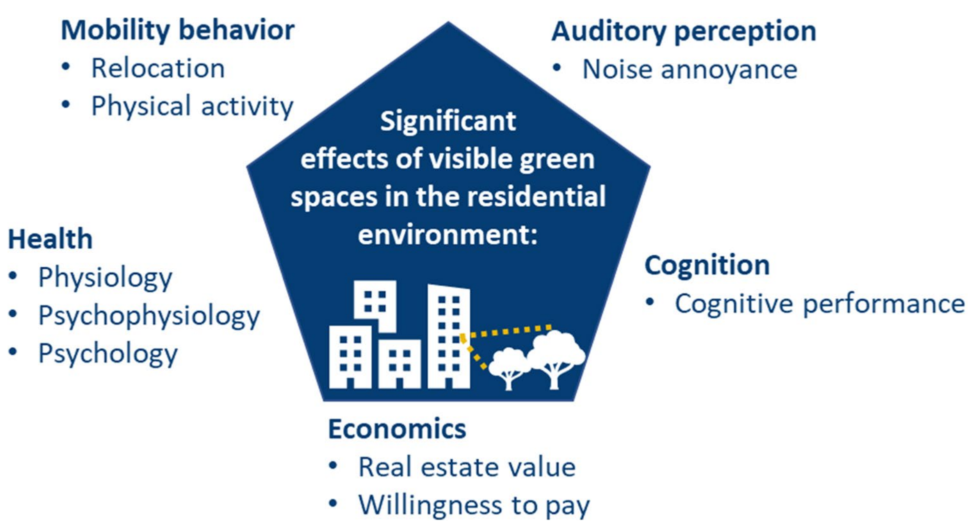

Fig. 1 Effect of visible urban green spaces in residential environments

potential for a whole building at different scale levels based on 3D modeling of the urban environment and simulation of window views (Fig. 2 (Bolte et al. 2024a)). The framework by Huang et al. (2024) allows a multi-level geostatistical analysis for the evaluation of socio-ecological justice of visual green spaces. This article presents the combination of the BGWVI and the geostatistical framework by Huang et al. (2024) as a first structured contribution to the integration of green space visibility in residential environments within the context of environmental justice research.

In this article, we initially delineate the methodological approach of the visibility analysis and the statistical evaluation of the spatial fairness of visible urban green spaces in the section "Materials and Methods". Subsequently, the section "Results" presents the distribution of green spaces in relation to different distances from the window. Furthermore, the article provides an in-depth analysis of the equity of visible green spaces and their correlation with the analysis indicators. The section "Discussion" includes a critical analysis of the socio-economic equity of green window views, implications for urban green space planning, and limitations of the analysis.

Materials and Methods

Study Area

The City of Cologne, Germany, is a district-free major city in the south of the federal state of North Rhine-Westphalia and had approximately 1.1 million inhabitants at the end of 2023 (City of Cologne 2024a). It serves as the seat of the Regional Government of Cologne and is situated in the Rhineland and Rhine-Ruhr metropolitan regions as well as the Cologne/Bonn region. The city is administratively divided into 86 city districts (see Fig. 3a and b; the names of the city districts can be found in Table 4 in the Appendix) (Metropolregion Rheinland e.V. n.d.; Region Köln/Bonn e.V. n.d.; Regional Government of Cologne 2024).

Approximately half of the 405 km^2 city area is built-up or has been designed as traffic areas. The undeveloped areas in Cologne are characterized by public parks, sports facilities, green spaces, and cemeteries, which collectively span approximately 11% of the total area. These green areas extend into an inner and outer green belt, the banks of the Rhine, and open spaces used for agriculture and horticulture purposes, accounting approximately 16% of the total area. Existing forest areas, constituting 18% of the total area, are predominantly located within the city districts of Rodenkirchen (208), Lindenthal (303), and Junkersdorf (306), in addition to the easternmost of the city (City of Cologne 2024c).

Data Sources

Visible Green Spaces

To model the urban environment of Cologne and conduct a green window view analysis using the BGWV, seven geodata sets were utilized. Table 1 lists the technical specifications for the data sources used for this purpose. The buildings and settlement typologies were obtained from the "Koeln Katalog," which includes typologies for "compact, sustainable, and liveable neighborhoods" (City of Cologne 2022). The data were provided by the Office for Urban Development and Statistics of the City of Cologne, with Duplex Architekten and De Zwarte Hond serving the copyright holders. As part of the analysis of the "Koeln Katalog," all residential buildings in Cologne were roughly classified in order to derive overarching,

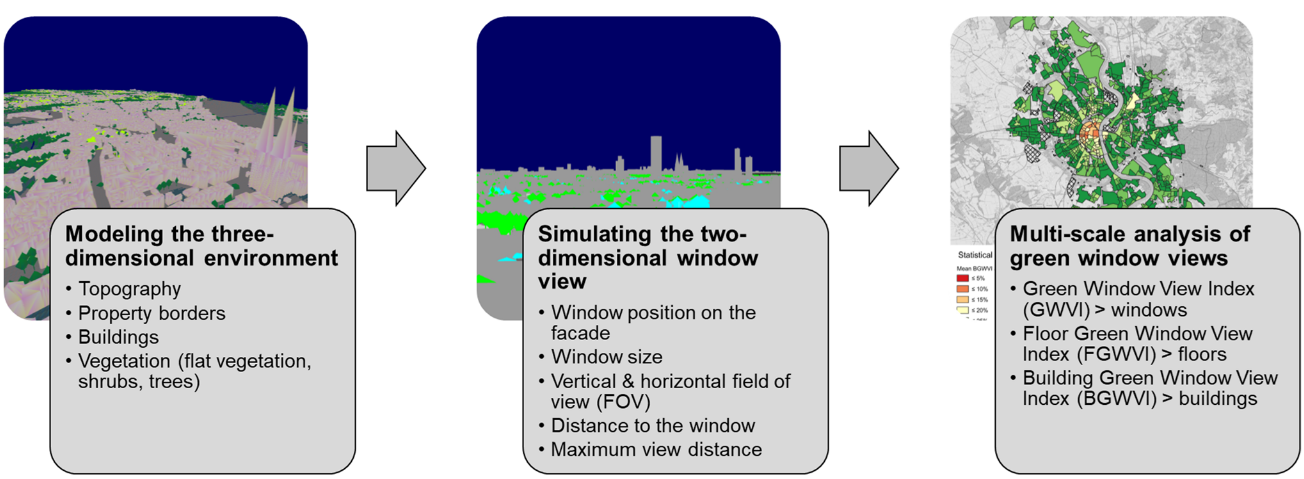

Fig. 2 Working principle of the BGWVI

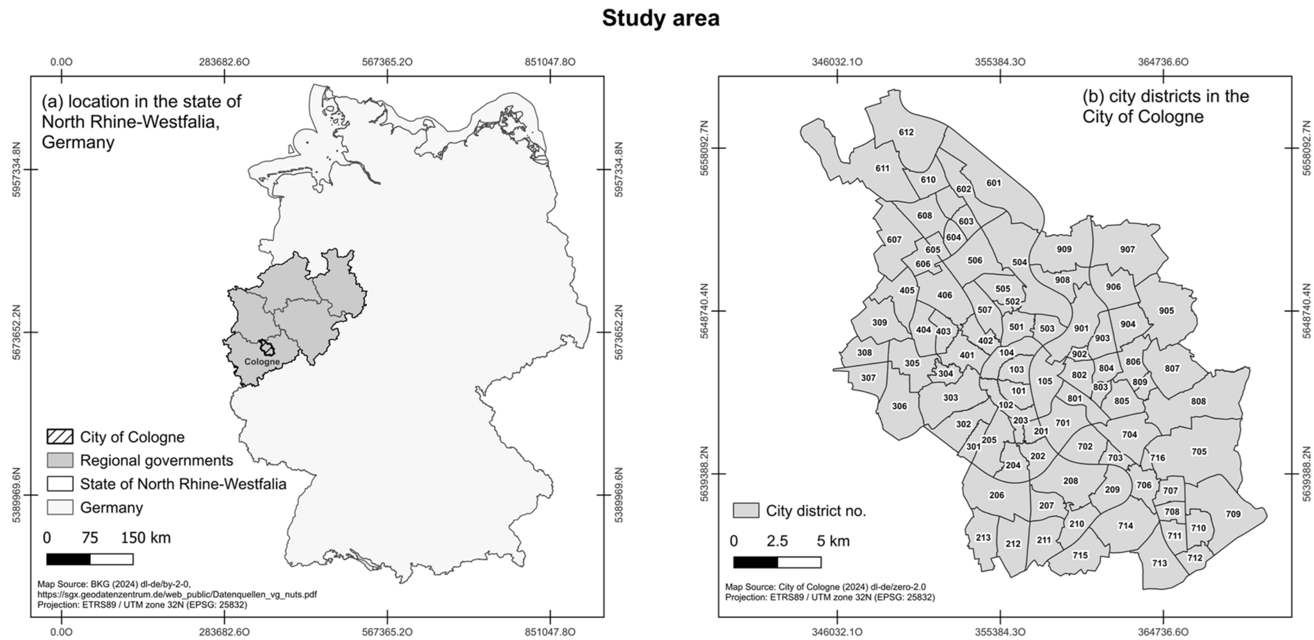

Fig. 3 Study area: City of Cologne is **a** located in the state of North Rhine-Westfalia, Germany, and is **b** administratively divided into 86 city districts

Table 1 Included geodata sets

Modeling target	Topography	Building objects	Building structure types	Property borders	Vegetation type	Flat vegetation	Tall vegetation
Data	Digital Terrain Model	3D Semantic City Model LoD2	Building and settlement typologies	ALKIS 2D Land Use Data	ALKIS 2D Land Use Data	Sentinel-2 L2A 2D Land Cover (B04/ B08)	Aerial LiDAR Point Clouds
Source	www.bezreg-koeln.nrw.de/geobasis-nrw	www.bezreg-koeln.nrw.de/geobasis-nrw	City of Cologne	www.bezreg-koeln.nrw.de/geobasis-nrw	www.bezreg-koeln.nrw.de/geobasis-nrw	https://browser.dataspace.copernicus.eu	www.bezreg-koeln.nrw.de/geobasis-nrw
Date	2023/01/02	2022/07/31	Summer 2021	2023/01/01	2023/01/01	2023/08/10	2023/01/02
Coordinate system	EPSG:25832	EPSG:25832	EPSG:25832	EPSG:25832	EPSG:25832	EPSG:3857	EPSG:25832
Height	DHHN2016	DHHN2016	/	/	/	/	DHHN2016
Spatial resolution	1 m	1 m	/	/	/	10 m/px	4–10 points/sqm
Accuracy	10 cm (height)	1 m (height); Cadaster (cm) (area)	Cadaster (cm) (area)	Cadaster (cm) (area)	Cadaster (cm) (area)	B04, B08	15 cm (height); 30 cm (area)
Format	.XYZ format	.gml format	.shp format	.NAS format	.NAS format	.TIFF format	.laz format

city-wide statements. The data set may contain scattered misclassifications as it was originally developed for a different purpose. Figure 11 in the Appendix shows two examples of misclassification. Figure 12 in the Appendix illustrates the distribution of the data set.

Socio-Economic Data

The data concerning the age structure of the population were derived from the municipal statistics of the City of Cologne. These annually published small-scale statistics contain demographic information on the population, disaggregated by the city's 86 city districts (City of Cologne 2024d). The mean age of the population is 42.2 years. The population is composed of approximately 5% of children under the age of six and approximately 18% of seniors aged 65 and over (City of Cologne 2024a).

The data regarding income distribution at the city district level are derived from the 2023 structural data survey of the City of Cologne (City of Cologne 2024b). The mean net household income is € 3208, while the mean income of households with children under the age of 18 is € 5379. However, this demographic has a higher risk of poverty, with a prevalence rate of 13%, compared to households without children, which have a risk of 8%. Individuals are considered to be at risk of poverty when their household income falls below the risk-of-poverty threshold, i.e., 60% of the average equivalized income (City of Cologne 2024b). Among the elderly populations, persons aged 65–80 living alone experience the most pronounced economic disadvantaged, with a mean disposable income of € 1975, significantly lower than the mean household income of € 3465 for couples in this age group (City of Cologne 2024b). The cited statistics reflect data as of December 31, 2023.

Analyzing Green Window View

In order to calculate the BGWVI, we first carried out a modeling and simulation step, as illustrated in Fig. 4. For further details regarding the individual steps, refer to Bolte et al. (2024a). The following subsections will focus on the specific alterations of the procedure that were implemented in the context of this case study.

The preprocessing was conducted using Q-GIS 3.34.3 and CloudCompare v2.13.beta. Subsequently, Q-GIS 3.34.3 was used for geostatistical analysis. The workstation ran on a 64-bit operating system, specifically WLS Ubuntu 20.04.6 LTS WLS on Windows 11 Pro. The workstation was equipped with a 12th generation Intel® Core™ i9-12900 K

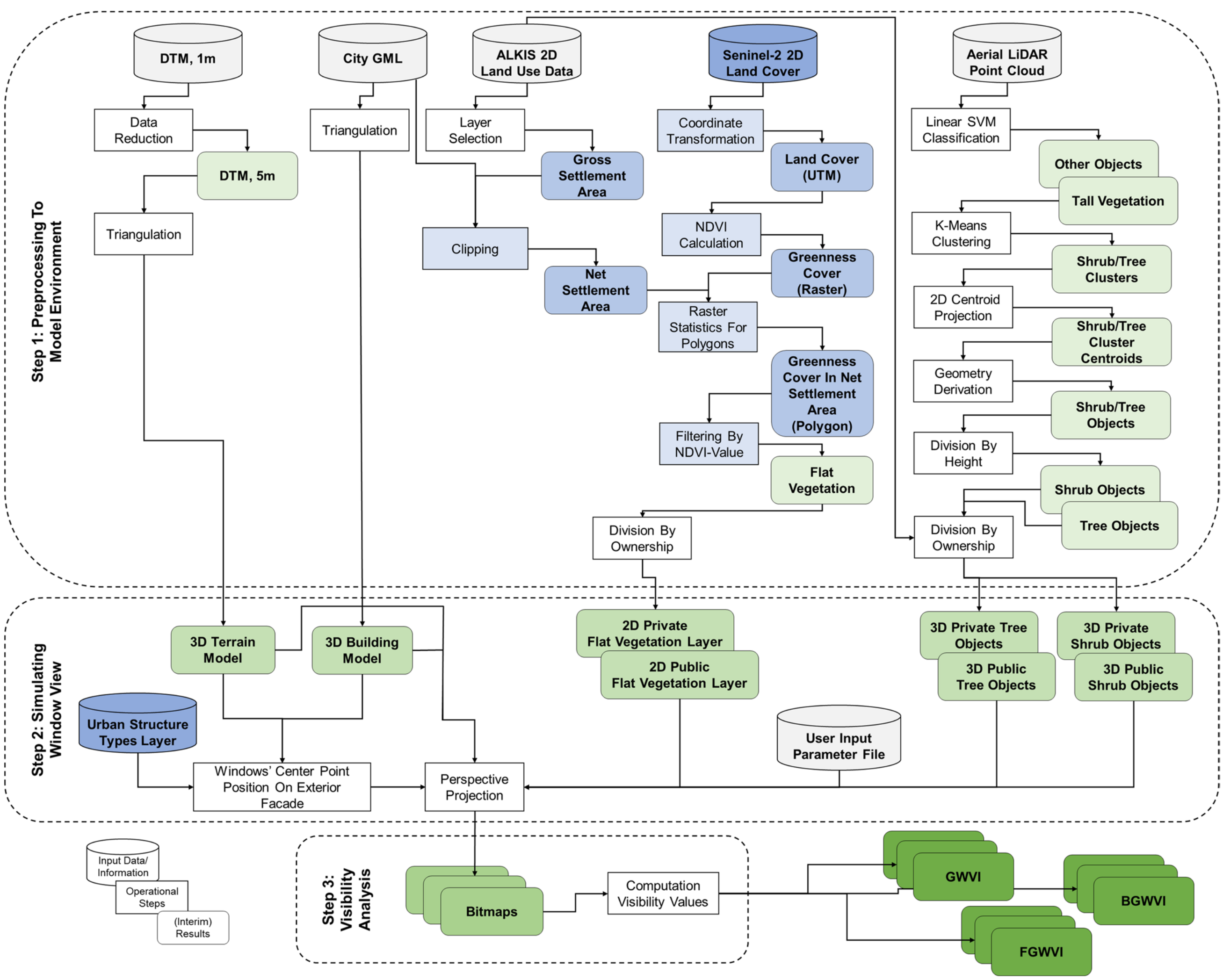

Fig. 4 Advanced workflow of the BGWVI (bluish segments represent adjustments) (Bolte et al. 2024a)

CPU with a base frequency of 3.20 GHz, a NVIDIA RTX A4500 graphics card, and a 128 GB SSD.

Modeling Urban Green Spaces

The modeling of the flat vegetation was performed in a multi-step process. The initial step involved the selection of 2D land use data from the official German property cadastre information system (ALKIS) (see Fig. 5).

In this study, we examined land use classes "residential area," "mixed-use area," and "special-purpose area," assuming the presence of partially vegetated land cover. In contrast, we further assumed complete vegetation was assumed for the remaining land use classes. To differentiate between sealed and vegetated open spaces, the land use classes, "residential area," "mixed-use area," and "special-purpose area," were clipped with the building footprints of the CityGML-based semantic 3D city model. This process was undertaken to obtain the net settlement area.

Two-dimensional land cover data, such as that provided by the Sentinel-2 satellite, was integrated into the workflow in order to model flat vegetation (Bolte et al. 2024b; Masoudi et al. 2024). The Normalized Difference Vegetation Index (NDVI) was calculated for the Sentinel-2 2D land cover data set, which was transformed to the EPSG:25832 coordinate system. In the case of Sentinel-2 data, the NDVI can be calculated in the following manner (custom-scripts.sentinel-hub 2024):

$$\mathrm{NDVI} = \frac{Band08 - Band04}{Band08 + Band04} \quad (1)$$

where *Band 08* corresponds to the near infrared while *Band 04* is reduced to the spectral range of visible red light. The NDVI normalizes the scattering of green leaves in the near infrared in relation to chlorophyll absorption in the visible red wavelength and assumes a value range from − 1 to 1. NDVI approaching − 1 indicate water, while values between − 0.1 and 0.1 are typically associated with barren areas consisting of rock, sand, or snow. NDVI ranging from 0.2 to 0.4 are characteristic of shrubs and grasslands, while values approaching 1 are an indication of temperate and tropical rainforests.

The NDVI values were transferred from the raster to the polygons of the net settlement area. Afterwards these polygons were filtered according to the mean NDVI being equal to or greater than 0.2 to identify green open spaces (Aryal,

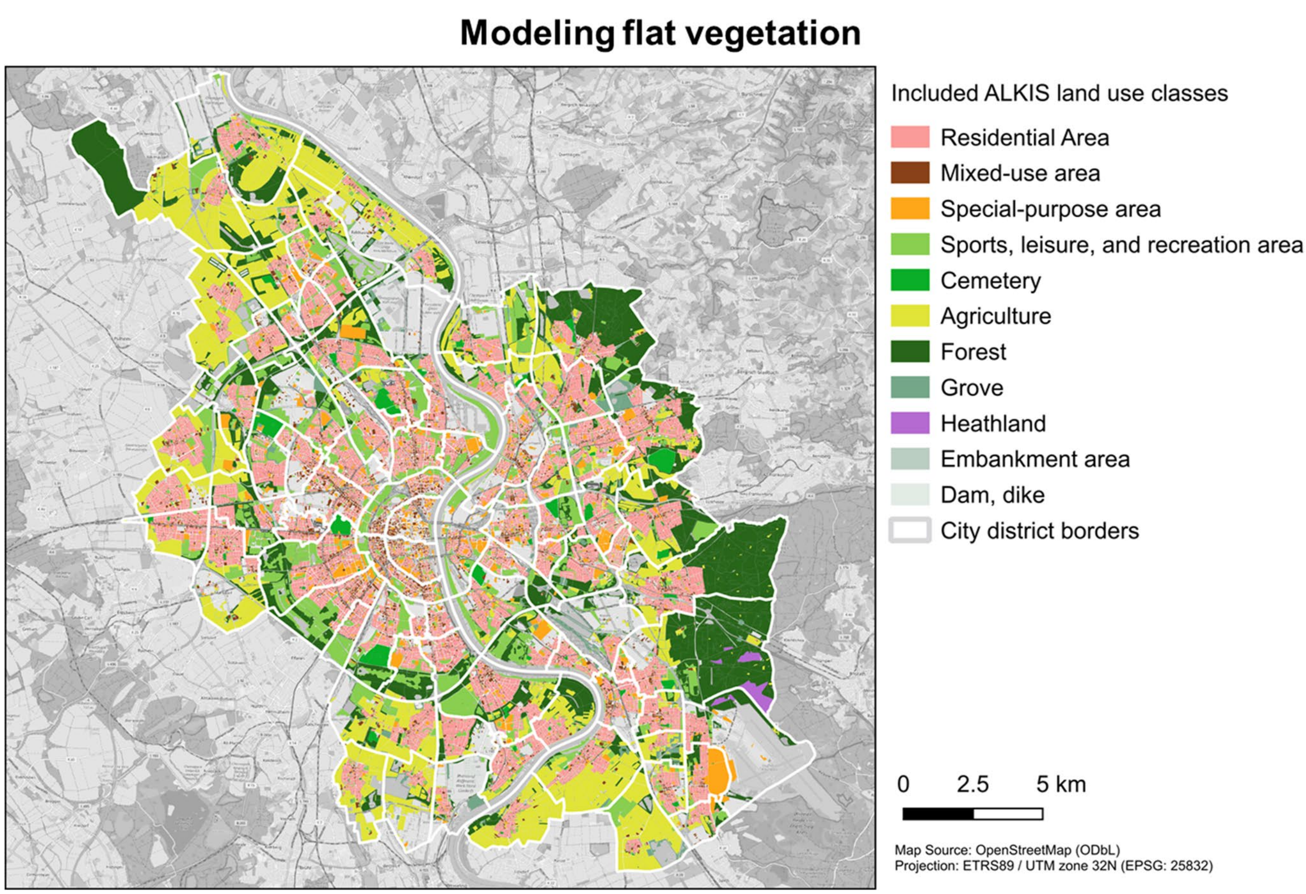

Fig. 5 Flat vegetation is modeled by integrating land use classes of the official German property cadastre information system (ALKIS)

Sitaula, and Aryal 2022; Bolte et al. 2024b; custom-scripts.sentinel-hub 2024). To model tall vegetation, linear support vector machine (SVM) was employed for the classification of LiDAR point clouds on a point-by-point basis, resulting in a mean accuracy of 98.1%.

Simulating Green Window Views for Residential Buildings on City District Level

In order to accurately simulate the window view, it is essential to have a clear understanding of the window location on a given building facade and the dimensions of the windows themselves. However, as the available semantic 3D city model CityGML with level detail (LoD) 2 lacks information regarding the position of windows, it is necessary to determine these first (Bundesamt für Kartographie und Geodäsie 2021).

To achieve this objective, Bolte et al. (2024b) identified ten different urban structure types. These categories included (1) village structure, (2) semi-detached and detached houses, (3) terraced houses, (4) linear structure, (5) housing estates, (6) large housing estates and high-rise buildings, (7) apartment buildings, (8) detached apartment buildings, (9) Wilhelminian style city centers, and (10) medieval city centers. The classification of these types was conducted in accordance with the methodology established by the City of Cologne (2022). The aforementioned study was conducted in the urban area of Bonn, Germany, and was inspired by the research by Dehbi et al. (2017). A total of 100 facades were identified, and the dimensions of their windows were recorded. These dimensions were then compared with the German industry standard DIN 18050 (DIN 18050 Fensteröffnungen für den Wohnungsbau (Window openings for residential construction) 1955). Finally, a building-specific facade was constructed for each urban structure type using the weighted arithmetic mean of the measured values (Bolte et al. 2024b). Figure 13 in the Appendix shows the building-specific facades and the corresponding figure-ground diagrams.

The generated information was utilized to identify green window views, employing the BGWVI formula (Bolte et al. 2024a):

$$\mathrm{BGWVI}_b = \sum_{i=1}^{m(b)} \mathrm{GWVI}_{id} * \frac{1}{m(b)}, \tag{2}$$

where the BGWVI is defined as the mean value of the GWVI for a given building b. The number of windows m depends on the investigated building. The GWVI is defined as the proportion of a visible vegetation area within the total field of view (FOV) when observing ith window at a given distance d to the window.

In this study, distances to the windows are defined as 10 cm, which represents standing directly behind the window, and 200 cm, which represents standing in the room with a maximum view range of 5000 m, respectively. For the subsequent geostatistical analysis, we used the centroids of the residential buildings. Table 5 in the Appendix provides detailed information regarding the derived window dimensions for the various urban structure types as well as the derived simulation parameters.

Evaluating Spatial Fairness of Visible Urban Green Spaces

Spatial Distribution

In order to examine the spatial distribution of BGWVI at the city district level, two geostatistical methodologies were employed. Firstly, the Global Moran's I index was employed as a test of the presence of spatial autocorrelation (Tiefelsdorf 2002). Furthermore, the Getis-Ord Gi* statistic was implemented to identify statistically significant hot spots and cold spots (Getis and Ord 1992). The interpretation of these statistics was contingent upon the z-value and p-value as outlined by Huang et al. (2024).

In order to conduct both the Global Moran's I and the hot spot analysis, a fixed distance band was implemented as a conceptual framework for analyzing spatial relationships. This approach utilizes the Euclidean distance to quantify the proximity of individual elements (Huang et al. 2024; Tong et al. 2020). The distance was set to 5000 m. Furthermore, a false discovery rate (FDR) correction was applied during the hot spot analysis to account for the multiple tests and spatial dependencies (Huang et al. 2024). Areas with high positive z-values and exceedingly low p-values are described as hot spots. The presence of spatial clustering of the BGWVI at the city district level is indicated if Global Moran's I values exceed zero. An elevated value signifies a more pronounced clustering tendency (Huang et al. 2024).

Gini Coefficient and Lorenz Curve

As defined by Yu et al. (2023) and Huang et al. (2024), the Gini coefficient is the ratio of the area between the line of equality and the Lorenz curve. The Gini coefficient was employed to evaluate the equity of the spatial distribution of green window views in each city district. The Lorenz curve is a graphical representation of the ordered cumulative distribution of green window views at the building scale. The x-axis represents the cumulative proportion of sample points, while the y-axis depicts the cumulative proportion of BGWVI at the building scale.

The Gini coefficient is a measure of statistical dispersion, taking values between 0 and 1. In general, a Gini coefficient of 0 represents perfect equity, indicating that the quantity of green window views is distributed equally across an area. Conversely, a Gini coefficient of 1 represents a state of perfect inequity, whereby all green window views are concentrated in a single area. Consequently, a Gini coefficient closer to 0 indicates a more equitable distribution of visual green space, whereas a coefficient closer to 1 represents a more inequitable distribution. The equation is provided below (Huang et al. 2024; Yang et al. 2020):

$$\text{Gini} = 1 + \left(\frac{1}{n}\right) - \left[\frac{2}{\overline{M} * n^2}\right] \sum_{i=1}^{n} \left[(n - i + 1) * M_i\right], \quad (3)$$

where Gini characterizes the degree of fairness in the spatial distribution of BGWVI across different city districts. The variable n denotes the amount of sample sites within each city district. $\overline{M}$ signifies the mean BGWVI in each city district. Finally, M_i represents the BGWVI of the ith sample site within a specific city district.

Share Index

The share index serves as an indicator for the comprehensive assessment of visible urban green space (i.e., the BGWVI at the city district scale) accessible to vulnerable populations. Initially, the proportion of visible urban green spaces accessible to a specified demographic was determined in relation to the total availability within the study area. This was calculated using the following equation, as outlined by Tang and Gu (2015):

$$R = \sum_{j=1}^{n} P_j * X_j * 100, \quad (4)$$

where R represents the proportion of the visible urban green space available to a vulnerable group, j denotes the number of city districts within the study area, P_j signifies the percentage of the population of a vulnerable group in city district j, and X_j is the ratio of the BGWVI of city district j to the sum of the BGWVI of each city district (Huang et al. 2024).

Next, the share index was calculated using the following equation, as described by Tang and Gu (2015):

$$F = \frac{R}{P}, \quad (5)$$

where P represents the percentage of the vulnerable group in the study area, while F denotes the share index. If F is greater than 1, it signifies that the share of visible urban green spaces for the vulnerable group exceeds the social mean share (Huang et al. 2024).

Location Entropy

The location entropy is defined as the ratio of the visible urban green space (BGWVI at city district scale) available to a vulnerable population within a city district to the total amount of green space within the entire study area. It is calculated as follows (Lou et al. 2022):

$$LQ_i = \frac{(T_i/P_i)}{(T/P)}, \quad (6)$$

where T_i is the BGWVI of city district i, P_i represents the vulnerable population in city district i, T is the sum of the BGWVI of each city district, and P denotes the vulnerable group within the study area (Huang et al. 2024).

The location entropy was classified into seven categories based on Lou et al. (2022) and Huang et al. (2024): < 0.2, 0.2–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0, 2.0–5.0, and > 5.0. In general, higher location entropy values are an indicative of greater access to visible urban green spaces for the vulnerable group within a city district. If the location entropy value exceeds 1, it can be inferred that the vulnerable demographic in the specified region has access to a greater quantity of visible urban green space than the average for the study area (Huang et al. 2024; Lou et al. 2022).

Results

Spatial Distribution of Visible Urban Green Spaces

As illustrated in Fig. 6, the spatial distribution and hot spot analysis of the BGWVI is depicted at the city district level. The classification of BGWVI is based on the work of Li et al. (2021), Tang et al. (2023), and Huang et al. (2024). The visual access to urban green spaces was quantified for a total of 160,532 buildings with residential purposes and the aggregated data were analyzed at the city district level (see Table 6 in the Appendix for the descriptive statistics of the individual urban structure types).

The mean BGWVI for a viewpoint located directly behind the window (10 cm) is, for the most part, relatively high in Cologne's urban area (Fig. 6a). Eleven city districts exhibit a mean BGWVI exceeding 35%, while the BGWVI is lowest in the central districts, reaching a maximum of 15% or 25%. The district-level values range from 9.75% (Altstadt/Nord, 103) to 48.02% (Hahnwald, 207), with a mean value of 30.89% and a median of 31.29%. The standard deviation is 5.18%.

These findings suggest that the city's residents have sufficient and satisfactory visual access to green spaces across the urban area. This finding aligns with prior studies'

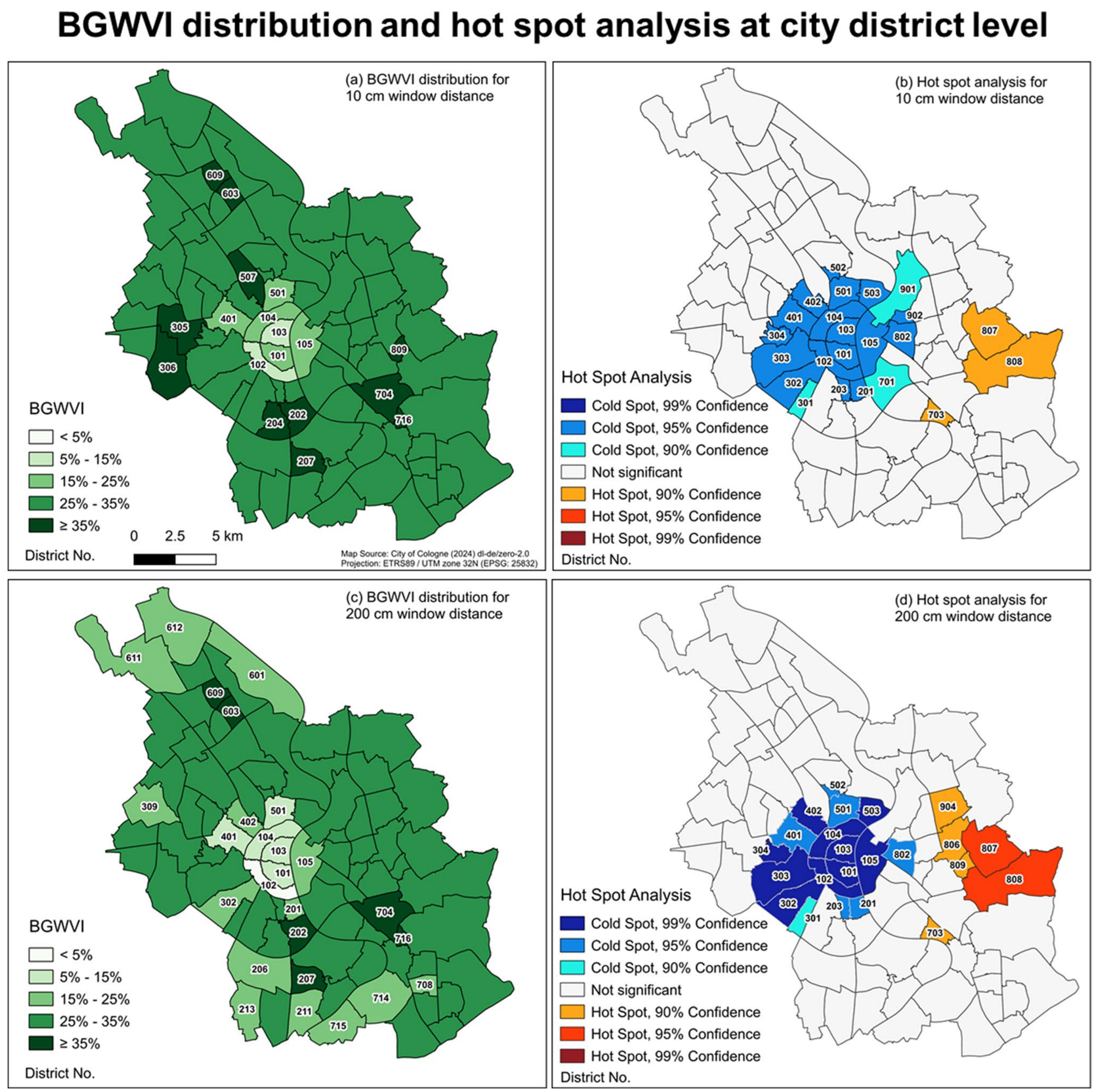

Fig. 6 **a** Eleven districts have a very satisfactory access to visible green spaces with a BGWVI exceeding 35%; **b** window views with a low proportion of visible green space are 90 to 95% likely to be found in central city districts; **c** the proportion of green space visible from a window in a central city district may not exceed 25%; **d** the probability of identifying a high proportion of visible green space within the window view in eastern city districts is estimated to be between 90 and 95%

conclusions that windows with a minimum of 30% green space have been associated with observer preferences and restorative effects (Aoki 1991; White et al. 2010).

From a viewpoint situated 200 cm from the window, the BGWVI range is 4.41% (Neustadt, Sued, 102) to 48.30% (Hahnwald, 207). The city-wide mean is 27.28%, with a median of 28.15%, and a standard deviation of 7.14% (Fig. 6c).

With regard to the spatial distribution of the data, it is evident that districts exhibiting relatively high BGWVI values (25 to 35%) continue to comprise the majority, with a mere six districts demonstrating a mean BGWVI above 35%. Additionally, districts in the north, south, west, and center exhibit a moderate proportion of 15–25% green window visibility, while the values in the center districts decline to below 5% green visibility.

Table 2 presents the results of the Moran's *I* indices, the *z*-values, and the *p*-values of the BGWVI at the district level for distances of 10 cm and 200 cm.

The findings in this study indicate a significant spatial clustering of the BGWVI in the urban area of Cologne, with a discernible pattern evident at both distances to the window. In both instances, the BGWVI values exhibiting the lowest levels are spatially clustered in the city center of Cologne. The observed clustering is statistically significant at the 90% level for the 10-cm distance (Fig. 6b) and at the 99% level for the 200-cm distance (Fig. 6d). These areas are primarily defined by the urban structure type characteristic of the historically developed medieval and Wilhelminian-style city center, block structured apartment buildings, and, on occasion, detached apartment buildings. The districts are distinguished by a higher building density and increased surface sealing, with a prevalence of mixed-use developments. The typical height of buildings is between three and four floors for apartment buildings and up to six floors for buildings in the city center. The availability of private green spaces is limited, with the majority of green space concentrated in the form of green inner courtyards. Urban green spaces are dominated by roadside greenery, in addition to smaller public open spaces and playgrounds (City of Cologne 2022).

The eastern districts of Cologne demonstrate a high degree of clustering of elevated BGWVI values, with a 90% confidence interval at a 10-cm distance (Fig. 6b) and a 90 to 95% confidence interval at a 200-cm distance (Fig. 6d). These areas are distinguished by a variety of urban structure types, including detached and semi-detached houses, village structure, row structure, and large housing estates including high-rise buildings. These areas are characterized by a relatively low building density and a minimal level of surface sealing. In terms of building height, the typical number of floors is one to two for village structures as well as for detached and semi-detached houses. In contrast, row structures typically reach four floors, while large housing estates and high-rise buildings generally have at least seven floors. Urban green spaces are distributed across various settings, including public parks and playgrounds, as well as privately owned plots where green distance areas between buildings, private gardens, and even agricultural land are commonplace (City of Cologne 2022).

Table 2 Results for presence of spatial autocorrelation in case study area for different distances

Index	City district level, 10 cm distance	City district level, 200 cm distance
Moran's *I* index	0.145	0.161
z-value	4.180	4.453
p-value	0.001	0.001

Equity of Visible Urban Green Spaces

As illustrated in Figs. 7a and 8a, the Lorenz curve and the Gini coefficient, respectively, demonstrate the distribution of visual access to urban green spaces in the urban region of Cologne.

The Gini coefficient values were 0.24 and 0.34, respectively, for the 10-cm and 200-cm distances. These values indicate that, from both perspectives, there is a relatively equitable distribution of visual access to urban green spaces in the urban region of Cologne. However, disparities in the equitable distribution become apparent at the district level, as demonstrated in Figs. 7b and 8b.

In the central districts, a Gini coefficient ranging from 0.4 to over 0.5 is observed. This range extends to the city center for a distance of 10 cm and expands to the surrounding districts of Bayenthal (201), Suelz (302), Ehrenfeld (401), Neuehrenfeld (402), and Nippes (501) for a distance of 200 cm to the window. These districts are primarily characterized by the urban structure types Wilhelminian-style city center and block-structured apartment buildings.

For both distances, the districts of Marienburg (202), Hahnwald (207), Seeberg (603), Gremberghoven (704), Finkenberg (716), and Neubrueck (809) demonstrate a spatially equal distribution of visible green spaces, as evidenced by a Gini coefficient of less than 0.2. With regard to urban morphology structures, these districts exhibit significant diversity. The districts of Marienburg and Hahnwald are distinguished by a preponderance of detached and semi-detached housing, as well as villa districts, complemented by extensive private gardens. Conversely, the districts of Seeberg and Finkenberg are notable for their large housing estates and high-rise buildings. The district Gremberghoven features a former railroad housing estate with self-catering gardens, reminiscent of the "garden city" concept. The urban structure of the district Neubrueck is characterized by a diverse range of housing types, including detached and semi-detached houses, terraced houses, large housing estates, and high-rise buildings (City of Cologne 2022; City of Cologne and NetCologne 2024).

Table 3 illustrates the equity of visual green spaces for vulnerable groups in the case study area at distances of 10 cm and 200 cm to the window.

The share index, which exceeds one, indicates that both children under the age of six and seniors at the age of 65 and above have a minimal higher access to visible green spaces than the overall social mean share.

In consideration of location entropy, spatially analogous patterns can also be discerned, as illustrated in Fig. 7c and Fig. 8c for children and Fig. 7d and Fig. 8d for senior citizens. Particular attention is directed towards values below 0.5 and above 2.0, as these indicate instances where children or senior citizens in the districts have only half or

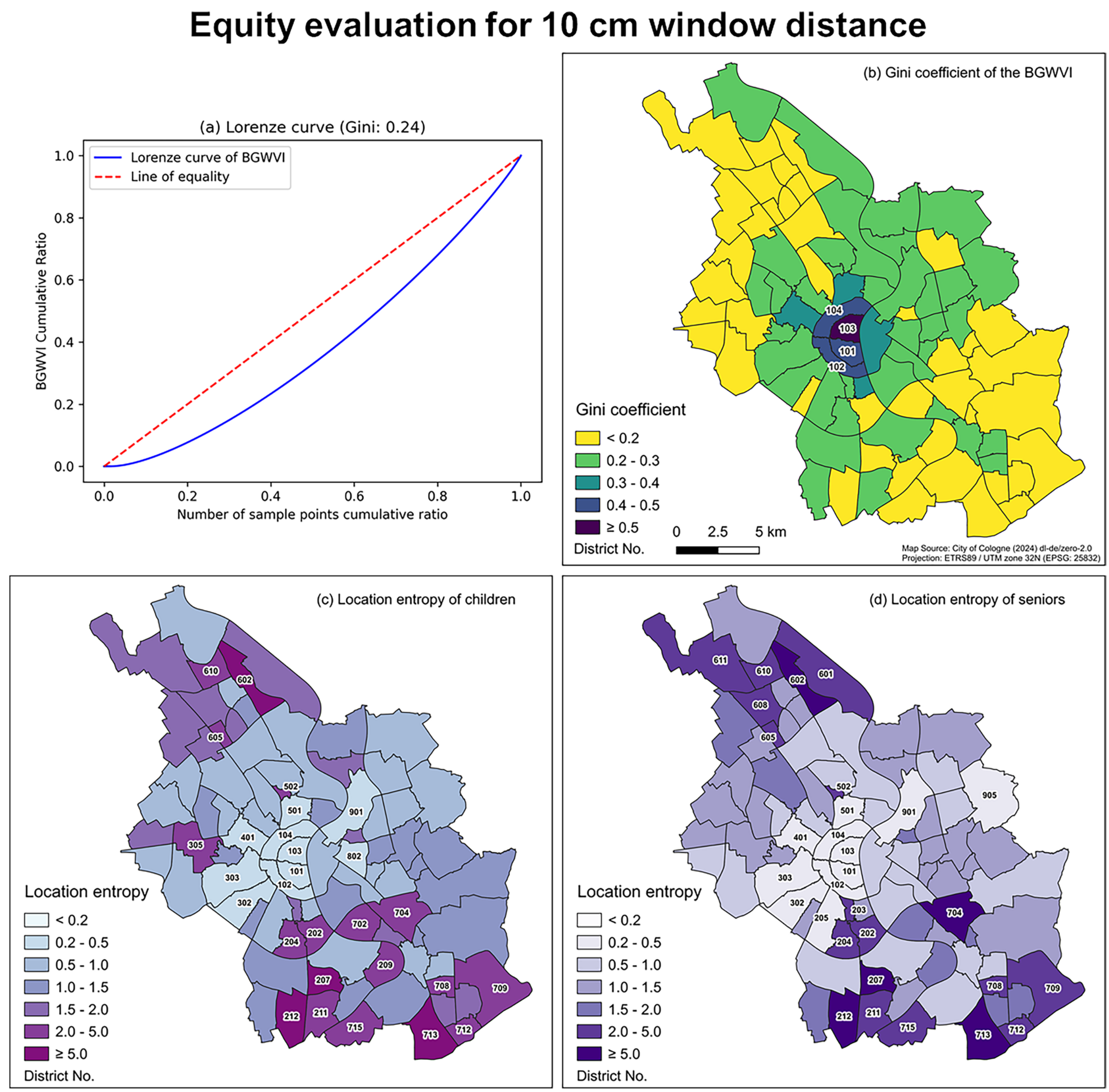

Fig. 7 **a** The city-wide distribution of green window views is relatively equitable; **b** a relatively equitable distribution of visible green spaces is present in areas located outside the central city districts (Gini < 0.4); the visual access to green spaces for **c** children and **d** seniors in northern and southern city districts is twice as high as the average (LQ > 2.0)

twice as much visual access to green spaces as the average (Huang et al. 2024).

For both vulnerable populations, central districts in Cologne exhibit a location entropy score of less than 0.5. In contrast, the southern, northern, and one western district, namely Muengersdorf (305), has a location entropy value greater than 2.0. The district of Hahwald (207) demonstrates the highest location entropy for children, with values of 11,693 and 13,323, respectively, at distances of 10 cm and 200 cm.

For senior citizens, the district of Libur (713) shows the highest location entropy, with values of 11,448 (at a distance of 10 cm) and 11,013 (at a distance of 200 cm). Libur is the district with the lowest population density in Cologne. It is distinguished by a village structure and extensive agricultural land use. The central district of

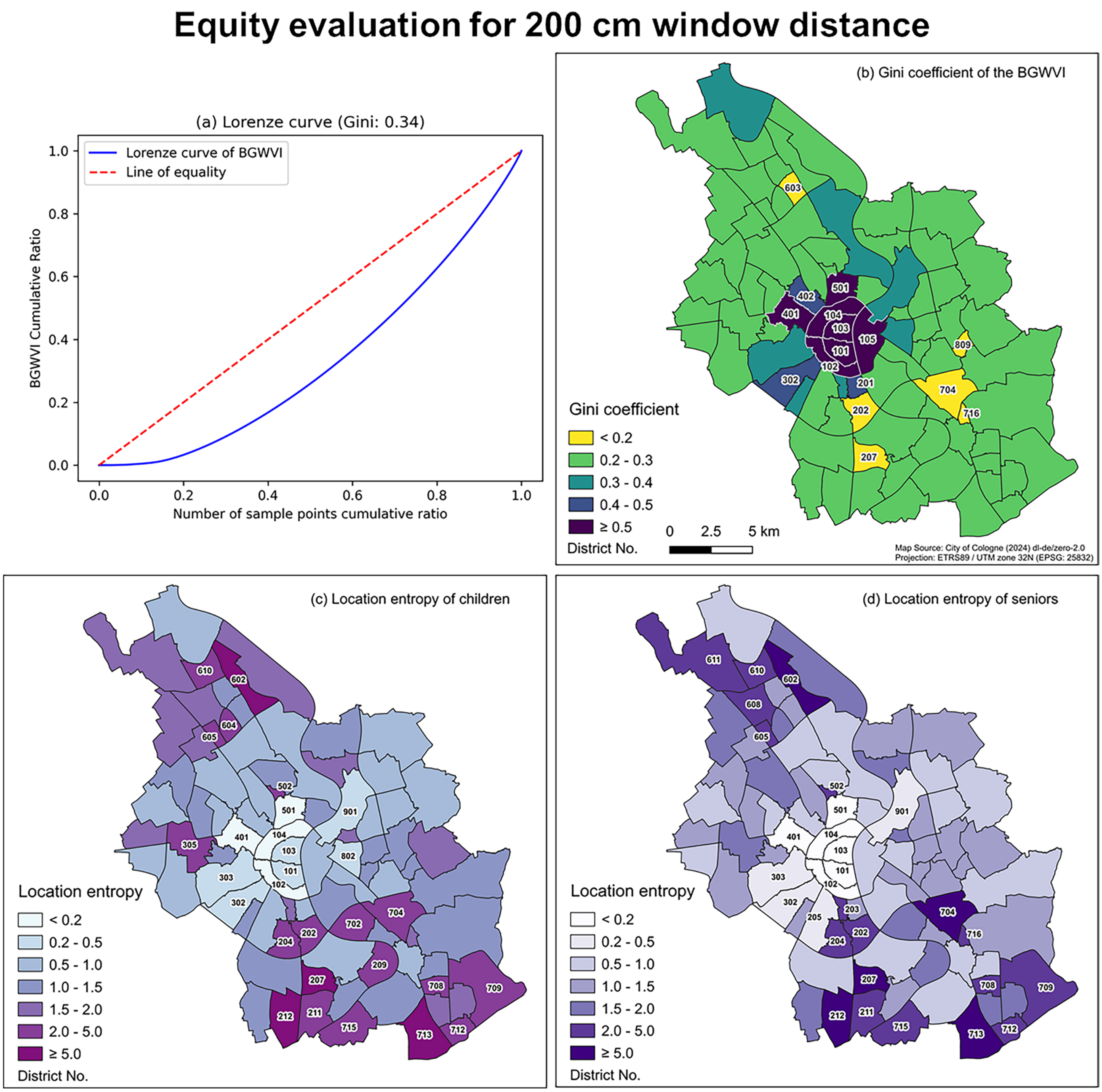

Fig. 8 **a** The city-wide distribution of visual access to urban green spaces is relatively equitable; **b** the distribution of visible green spaces in the central city districts is relatively inequitable (Gini > 0.4) **c** children and **d** seniors in the central city districts have half as much visual access to green spaces as the average (LQ < 0.5)

Table 3 Equity of visual green spaces for vulnerable groups in case study area for different window distances

Share index	City district level, 10 cm distance	City district level, 200 cm distance
Children < 6 yrs	1.06	1.07
Seniors ≥ 65 yrs	1.08	1.09

Neustadt/Sued (102) has the lowest location entropy for both children and senior citizens, with values of 0.219 (children, 10-cm distance), 0.073 (children, 200-cm distance), 0.250 (senior citizens, 10-cm distance), and 0.083 (senior citizens, 200-cm distance). The urban structure of this district is predominantly characterized by a Wilhelminian-style city center.

Correlation Among Evaluation Indicators

At the district level, the correlation between the BGWVI, the Gini coefficient, and the mean net household income was carried out. The resulting correlation matrices with significance levels for distances of 10 cm and 200 cm are illustrated in Fig. 9a and b, respectively.

In this case study, the mean net household income was employed as a representative indicator of the socio-economic status of the population. The spatial distribution of this variable is illustrated in Fig. 10. Districts with fewer than 30 cases were excluded from the analysis, as the data set is insufficient to yield meaningful results.

A low correlation was observed between the BGWVI and the mean net household income when the viewpoint was situated directly behind the window ($r = 0.22$, $p < 0.05$). This finding suggests that individuals with a higher socio-economic status tend to reside in areas with a greater availability of visible green spaces. This correlation demonstrates a decline in significance, reaching lower positive value that is not statistically significant for a position within the room ($r = 0.09$, $p > 0.1$).

A significant negative correlation is also evident between the Gini coefficient and the BGWVI for both distances to the window ($r = -0.88$, $p < 0.01$), suggesting that individuals residing in districts with restricted green space within their window view are more likely to encounter an unequal distribution of visual green space within their residential environment. However, this result is a consequence of the fact that the Gini coefficient is calculated based on the BGWVI.

Furthermore, a significant moderate positive correlation is identified between the proportion of children and seniors in the district and the BGWVI. At a distance of 10 cm, the correlation was $r = 0.43$, $p < 0.01$ for children and $r = 0.40$, $p < 0.01$ for seniors. Additionally, at a distance of 200 cm, the correlation was $r = 0.45$, $p < 0.01$ for children and $r = 0.40$, $p < 0.01$ for seniors. However, a significant negative correlation was identified between the number of inhabitants and the location entropy for children (both distances: $r = -0.54$, $p < 0.01$) and seniors (both distances: $r = -0.57$, $p < 0.01$) (Kuckartz et al. 2013, p. 213).

Discussion

Socio-Economic Equity of Green Window Views

The findings indicate that the city-wide mean BGWVI is 31%, suggesting that access to visual green space is satisfactory across the city (Aoki 1991; White et al. 2010). Notwithstanding an indoor viewpoint and a reduced mean value of over 27%, visual access to green spaces in Cologne is more satisfactory in comparison to national and international studies. For instance, a case study in Bonn, Germany, analyzed the BGWVI in approximately 63,000 residential buildings, determining a city-wide average BGWVI of 25.19% at a distance of 10 cm from the window (Bolte et al. 2024b).

Related to international studies, the mean value in Fuzhou, China (Huang et al. 2024) was 24%, in Beijing, China (Dong et al. 2018), it was 17.1%, and in Hong Kong, it was 16% (Lu 2019). However, it is important to note that the comparative international studies only examine visible street-level green spaces in a limited number of urban case studies. This study represents one of the first comprehensive investigations at the city-wide level, with a detailed

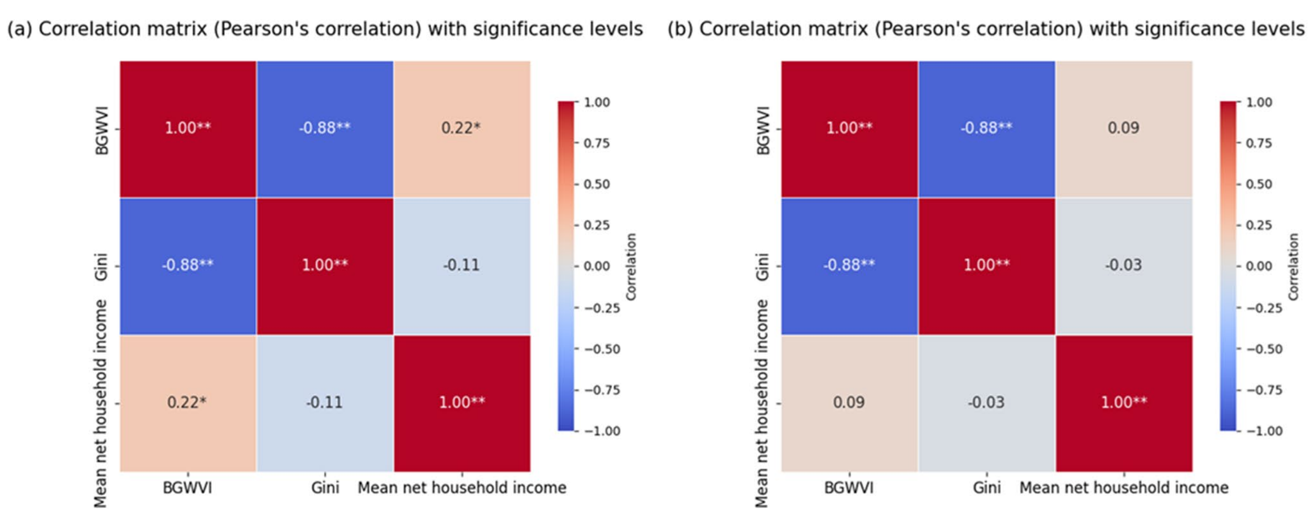

Fig. 9 Correlation matrix between BGWVI, Gini coefficient, and mean net household income based on Pearson's correlation with significance levels *$p < 0.05$, **$p < 0.01$: **a** 10-cm distance; **b** 200-cm distance

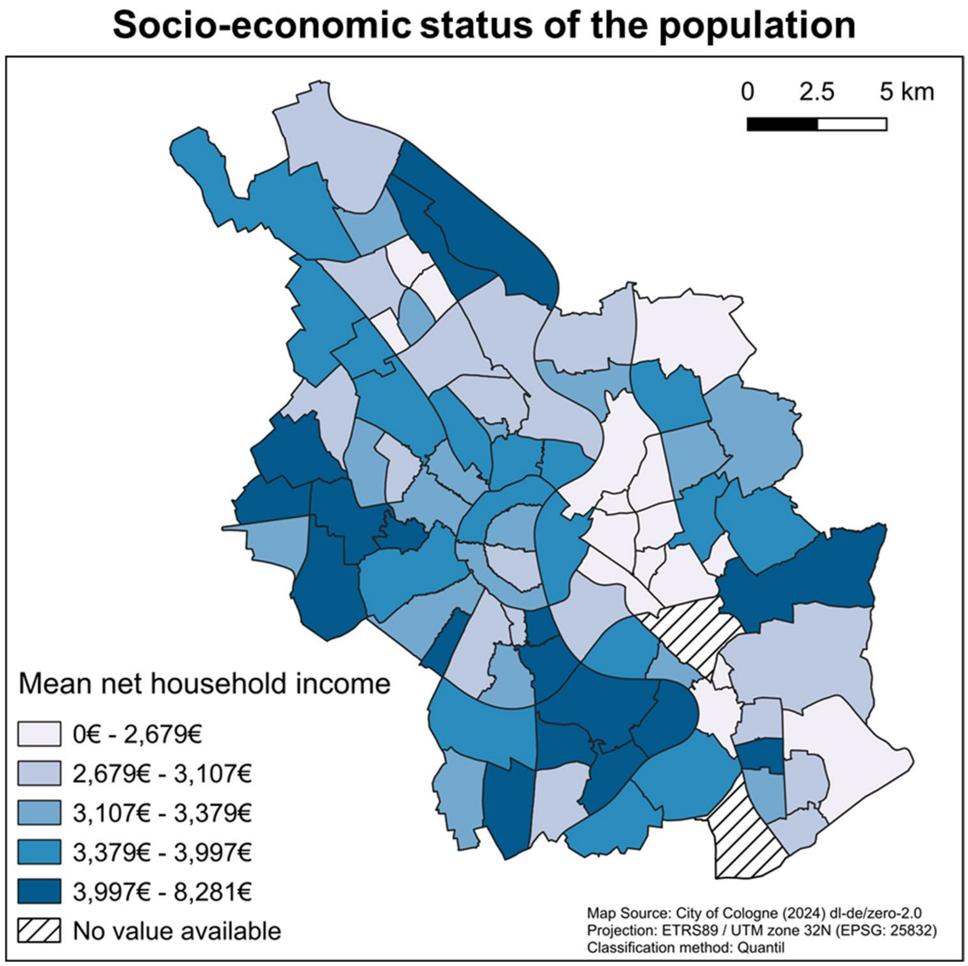

Fig. 10 Socio-economic status of the population in the City of Cologne represented by the mean net household income at city district level

differentiation by district and urban structure type, to assess the visibility potential of green spaces in residential environments for window views. A comparison is therefore only possible to a limited extent.

The Gini coefficient of 0.24 (10-cm distance) and 0.34 (200-cm distance) are lower than that observed in the green street view investigation by Huang et al. (2024), which yielded a Gini coefficient of 0.36. Furthermore, these Gini coefficients are lower than those calculated for the City of Cologne in previous studies. When analyzing the availability of green spaces for the population, the Gini coefficient reached approximately 0.4 (Weigand et al. 2023), while when assessing the provision of green spaces per capita, the Gini coefficient exceeded 0.5 (Wüstemann, Kalisch, and Kolbe 2017). These findings suggest that visibility as a supplementary access type plays a key role in ensuring an equitable distribution of accessible green spaces.

The study by Wüstemann, Kalisch, and Kolbe (2017) lends support to the assertion that the share index for children and senior citizens, which is minimally above one, results in minimally greater access to visible green spaces for these vulnerable population groups in comparison to the overall social mean share. This is evidenced by a significantly positive correlation between age of individuals (at 65 years and above) and the presence of children in the household and the amount of available green space.

The low positive correlation between the BGWVI and the mean net household income of $r = 0.22$ suggests a small advantage in visual access to green spaces in residential areas for the population with a higher socio-economic status (Huang et al. 2024). This phenomenon is further substantiated by studies on real estate valuation, which demonstrate that the price of real estate sales increases due to green window views (Chen and Jim 2010; Gu, Wang, and Liu 2021; Hui and Liang 2016; Jim and Chen 2006) and the willingness to pay a higher price for the purchase (Hui, Zhong, and Yu 2012). This trend can also be quantified using metrics such as square meters ratio of green space per household in Germany (Wüstemann, Kalisch, and Kolbe 2017). However, a significant correlation between the mean net household income and the Gini coefficient, as demonstrated by Huang et al. (2024), is absent in the City of Cologne. This finding indicates that income does not exert a significant influence on the equal distribution of visible green space within the city.

Implications for Urban Green Space Planning

The significant presence of high BGWVI values across diverse urban structure types (refer to Table 6 in the Appendix) indicates that the implementation of existing guidelines for the provision of accessible green spaces in residential areas has a positive impact on visual access (Blum et al. 2023; Gälzer 2001, pp. 61–68; Richter 1981, pp. 73–76). However, given that these results represent the inaugural structured visibility values for various categories of residential buildings, further studies are required to ascertain whether the values represent morphologically determined patterns or whether they are the consequence of intensive local green space planning.

As the number of floors in residential buildings increases, the amount of visible green space decreases, a phenomenon observed across all urban structure types (refer to Table 6 in the Appendix).

In a manner analogous to that observed in Cologne, the BGWVI for visible green spaces in Bonn is lowest in the city center. Furthermore, a low negative correlation between various urban density values and the BGWVI was also evident in Bonn. The correlation between the ratio of the floor area of residential buildings and the neighborhood area (neighborhood density), or between the ratio of the floor area of residential buildings and the sum of the gross residential area and the gross area of mixed use (residential density) to the BGWVI of urban green spaces was negative in each case ($r_s = -0.26$, $p < 0.05$). When the presence of exclusively flat vegetation was considered, the negative correlation between the BGWVI and neighborhood density increased to $r_s = -0.39$ at $p < 0.01$ and residential density to $r_s = -0.38$ at $p < 0.01$. A differentiation of BGWVI for individual urban structure types was not available for Bonn (Bolte et al. 2024b).

Furthermore, the BGWVI is characterized by a significant decline in central city districts that are affected by elevated Gini coefficients.

Giving these findings, it is recommended to prioritize vertical greening in urban green space planning and inner urban development processes, such as additional roadside greenery, facade greening, and roof greening (Bolte et al. 2024b; Chettry 2023). This approach is necessary to ensure a comprehensive and equitable access to green spaces for diverse population groups and to facilitate sustainable and resilient urban development. However, it is crucial to consider the potential consequences of green gentrification, which is defined as the process of spatial and structural upgrading in neighborhoods, accompanied by increases in real estate prices. These increases are derived by the intensification and improvement of green spaces. The process of green gentrification has the potential to result in unintended consequences, including the limitation of available visual access for individuals with low socio-economic status (Ali et al. 2020; Anguelovski et al. 2018; Friesenecker et al. 2024; Rigolon and Németh 2019).

Limitations

The present study addresses the issue of age as a form of vulnerability among a particular population and highlights the need for comprehensive analysis that includes gender and health status to assess the distributional equity of visible green spaces for vulnerable social groups. It is therefore essential that further research is conducted on the visual green experiences of women and physically disabled individuals to attain a comprehensive understanding of the quality of resilient green space planning (Pijpers and van Melik 2020; Städtebau für Frauen und Männer (Urban planning for women and men) 2006; United Nations 2015). Studies examining the green window view of hospitals and rehabilitation centers have demonstrate that green window views also have a beneficial effect on the well-being of patients (Gao and Zhang 2020; Raanaas et al. 2012; Ulrich 1984).

In order to conduct a comprehensive examination of visibility potential at street or building level, it is essential to implement a classification of residential buildings, as the data utilized to ascertain urban structure types lacks sufficient specificity for small-scale analysis (see subsection "Data Sources"). The classification approaches that are suitable for practical use are based on Random Forest classification, Fully Convolutional Neural Networks semantic segmentation, or Support Vector Machines (Droin, Wurm, and Sulzer 2020; Hecht 2013; Henn et al. 2012). Unmanned aerial systems (UAS) can also be used to support detailed urban mapping (Nagy et al. 2024).

The visibility analysis surrounding the BGWVI is grounded in the theoretical framework of space syntax, which has been extensively used in the domains of landscape and cityscape analysis, particularly within the fields of landscape and spatial planning (van Nes and Yamu 2021). However, a definitive validation of the window simulation is not feasible, as the requisite CityGML data for our case study is only available at Level of Detail (LoD) 2 (Bundesamt für Kartographie und Geodäsie 2021; Dehbi et al. 2017; Wysocki, Hoegner, and Stilla 2024).

The lack of available data regarding the location and dimensions of windows necessitates the empirical determination of typical building facades for each urban structure type and their assumption in advance. It can thus be inferred that the utilization of photographs of individual window views as a ground truth for the intersection over union method is an unsuitable approach. Given that the modeling of the vegetation achieved an average accuracy of 98.1%, it can be assumed that the simulation results are fit for purpose.

A comparison of the simulation outcomes with ratings of window views for entire buildings, collected using citizen science, is recommended for a comprehensive final evaluation. This approach enables the collection of sufficient ground truth data from residential buildings that are not openly available for research purposes (A.-M. Bolte, Moghadas, and Kötter 2023). However, the mentioned evaluation procedure is beyond the scope of the present article and must be carried out in a subsequent study. One potential platform for this is the existing crowdsourcing initiative, "Colouring Dresden," in the federal state of Saxony Germany, which collects building data with the help of citizen science (Leibniz-Institut für ökologische Raumentwicklung e. V. 2024).

Conclusion

In this study, we examined green window views in residential buildings to identify patterns of distributive equity for seniors and children, considering their socio-economic status for the first time. We combined the methodology around the BGWVI and the methodological framework of Huang et al. (2024) to measure the visibility potential of green spaces for buildings in order to geostatistically analyze the equity of the spatial distribution of visual urban green spaces. Using the Gini coefficient, the share index, and the location entropy, an evaluation of the access to visible green spaces according to socio-economic status and age group was carried out at the city district level for the City of Cologne, Germany. Low values of the BGWVI occur mainly in the city center. The mean BGWVI is 30.89% when the observer is located directly behind the window while it reaches 27.28% when the observer is standing in the room. The spatial distribution of BGWVI is relatively equal in the study area. Considering the proportion of vulnerable groups in the district, an unequal distribution of visible green spaces can be measured, especially in the central districts. However, compared to the social mean share, children and seniors have slightly better access to visible green spaces. The influence of the mean net household income on green window views is also low. The results allow a comprehensive evaluation of existing green space planning in a major German city, including the influence on equitable social and ecological access to visible green spaces for vulnerable groups in the residential environment, which overall strengthens promoting sustainable and resilient urban development.

Appendix

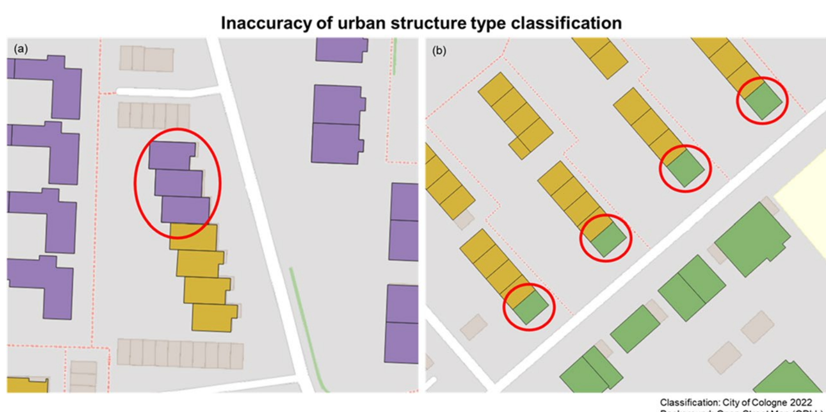

Fig. 11 Two examples of misclassification: The urban structure type "terraced houses" (yellow) is incorrectly classified as **a** "semi-detached and detached houses" (purple) or as **b** "detached apartment buildings" (green)

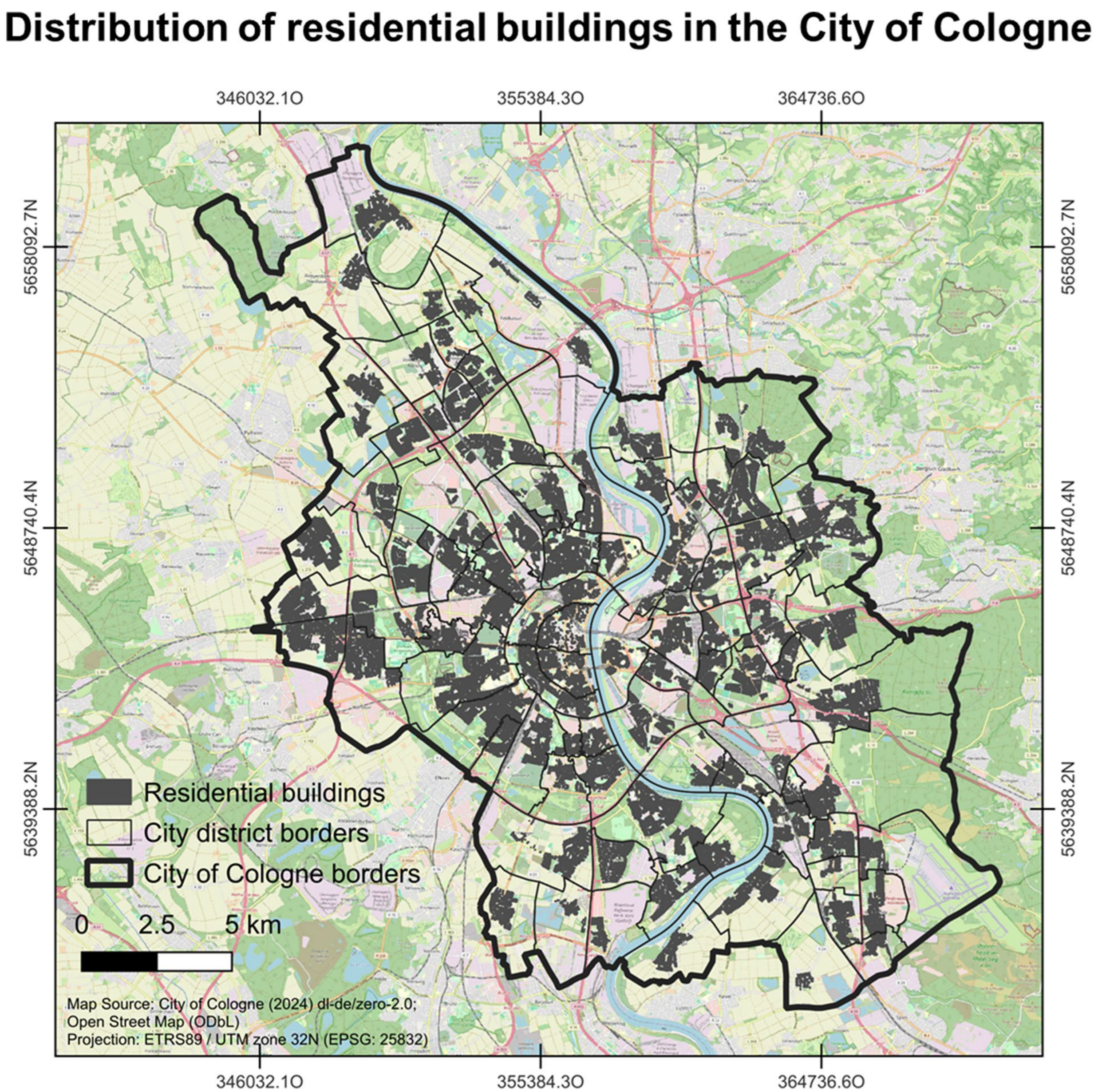

Fig. 12 A total of 160,532 buildings with residential purposes in the City of Cologne are included in the visibility analysis

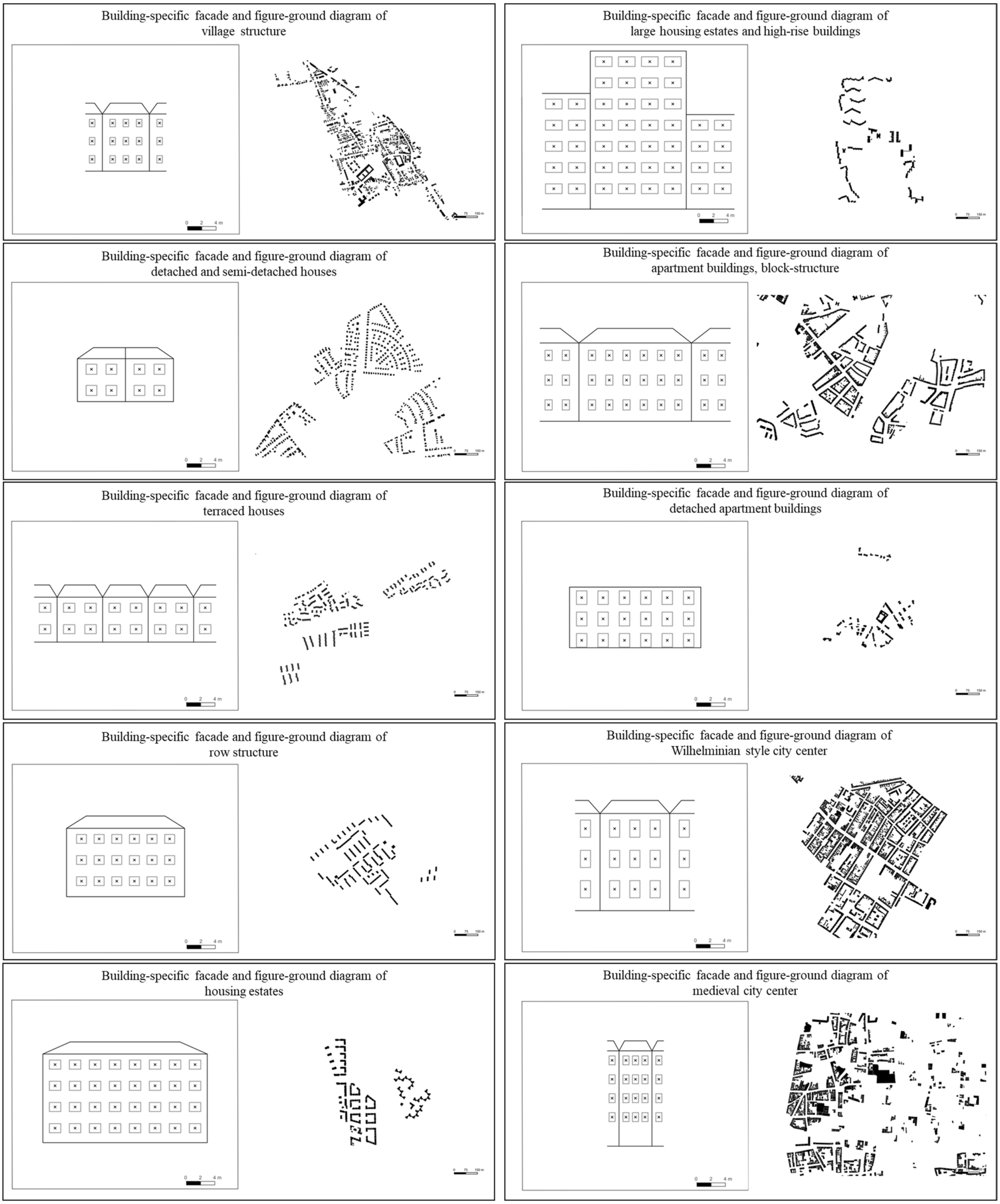

Fig. 13 Building-specific facades and figure-ground diagrams of urban structure types

Table 4 Investigated city districts of Cologne

City district no	City district name
101	Altstadt-Süd
102	Neustadt-Süd
103	Altstadt-Nord
104	Neustadt-Nord
105	Deutz
201	Bayenthal
202	Marienburg
203	Raderberg
204	Raderthal
205	Zollstock
206	Rondorf
207	Hahnwald
208	Rodenkirchen
209	Weiß
210	Sürth
211	Godorf
212	Immendorf
213	Meschenich
301	Klettenberg
302	Sülz
303	Lindenthal
304	Braunsfeld
305	Müngersdorf
306	Junkersdorf
307	Weiden
308	Lövenich
309	Widdersdorf
401	Ehrenfeld
402	Neuehrenfeld
403	Bickendorf
404	Vogelsang
405	Bocklemünd/Mengenich
406	Ossendorf
501	Nippes
502	Mauenheim
503	Riehl
504	Niehl
505	Weidenpesch
506	Longerich
507	Bilderstöckchen
601	Merkenich
602	Fühlingen
603	Seeberg
604	Heimersdorf
605	Lindweiler
606	Pesch
607	Esch/Auweiler
608	Volkhoven/Weiler
609	Chorweiler
610	Blumenberg
611	Roggendorf/Thenhoven
612	Worringen
701	Poll
702	Westhoven
703	Ensen
704	Gremberghoven
705	Eil
706	Porz
707	Urbach
708	Elsdorf
709	Grengel
710	Wahnheide
711	Wahn
712	Lind
713	Libur
714	Zündorf
715	Langel
716	Finkenberg
801	Humboldt/Gremberg
802	Kalk
803	Wingst
804	Höhenberg
805	Ostheim
806	Merheim
807	Brück
808	Rath/Heumar
809	Neubrück
901	Mülheim
902	Buchforst
903	Buchheim
904	Holweide
905	Dellbrück
906	Höhenhaus
907	Dünnwald
908	Stammheim
909	Flittard

Table 5 BGWVI analysis parameters for empirically determined building-specific facades

Urban structure type	Spacing betw. window centers and ground	Lateral spacing betw. window centers and facade edge	Lateral spacing betw. window centers	Floor height	Window width	Window height	Window ratio	Vertical fov*
Village structure	168 cm	144 cm	187 cm	256 cm	78 cm	104 cm	0.75	29.1°
Detached and semi-detached houses	158 cm	198 cm	281 cm	300 cm	152 cm	143 cm	1.06	39.5°
Terraced houses	183 cm	171 cm	302 cm	300 cm	161 cm	127 cm	1.27	35.2°
Row structure	220 cm	212 cm	249 cm	300 cm	141 cm	125 cm	1.13	34.7°
Housing estates	205 cm	172 cm	283 cm	300 cm	161 cm	128 cm	1.25	35.6°
Large housing estates and high-rise buildings	288 cm	191 cm	326 cm	300 cm	236 cm	138 cm	1.72	37.9°
Apartment buildings, block-structure	232 cm	184 cm	244 cm	350 cm	101 cm	144 cm	0.71	39.5°
Detached apartment buildings	105 cm	172 cm	302 cm	300 cm	148 cm	193 cm	0.77	51.4°
Wilhelminian style city center	305 cm	206 cm	287 cm	430 cm	144 cm	244 cm	0.59	62.8°
Medieval city center	412 cm	98 cm	134 cm	268 cm	86 cm	126 cm	0.68	35.0°

*Considering observer's distance to window of 200 cm. At 10 cm distance applies: visual field with view width of 35 cm, view height of 24 cm, view ratio of 1.45, and vertical fov of 100° (Grehn 2019)

Table 6 Descriptive statistics of visible green spaces for urban structure types

Urban structure type	N	Min BGWVI		Max BGWVI		Average BGWVI		Median BGWVI		Standard deviation BGWVI		Mean FGWVI changes per higher floor*	
		10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance
Village structure	13,836	0.00%	0.00%	82.85%	88.29%	28.92%	24.25%	29.04%	22.97%	11.80%	13.09%	−6.52%	−4.94%
Detached and semi-detached houses	43,766	0.00%	0.00%	92.30%	99.48%	32.94%	29.74%	32.20%	28.29%	11.03%	12.66%	−5.50%	−5.07%
Terraced houses	27,843	0.00%	0.00%	93.06%	98.59%	33.41%	30.53%	33.20%	29.03%	11.40%	13.31%	−6.66%	−5.69%
Row structure	5133	0.42%	0.00%	80.91%	84.39%	38.12%	35.63%	37.63%	35.38%	12.43%	14.54%	−5.64%	−4.53%
Housing estates	6588	0.10%	0.00%	85.78%	87.48%	33.32%	27.30%	32.76%	24.93%	11.53%	15.01%	−6.00%	−4.38%
Large housing estates and high-rise buildings	1632	0.07%	0.00%	70.15%	84.56%	34.65%	33.33%	34.88%	33.19%	11.76%	12.89%	−4.84%	−1.74%
Apartment buildings, block-structure	26,642	0.00%	0.00%	100.00%	85.54%	27.95%	27.01%	27.95%	25.79%	12.47%	14.04%	−5.06%	−4.04%
Detached apartment buildings	14,313	0.00%	0.00%	86.23%	99.93%	33.28%	31.05%	32.88%	29.88%	11.68%	12.71%	−5.27%	−4.83%
Wilhelminian style city center	17,841	0.00%	0.00%	100.00%	9.38%	18.70%	1.88%	16.74%	1.68%	13.79%	1.41%	−4.01%	−0.07%
Medieval city center	2938	0.00%	0.00%	63.60%	65.45%	12.50%	10.61%	7.44%	6.66%	13.82%	11.79%	−3.12%	−1.15%

*For buildings with at least 2 floors and a FGWVI (Bolte et al. 2024a) of at least 5%

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Author Contribution AMB: conceptualization. AMB: methodology. AMB: formal analysis and investigation. AMB: writing—original draft preparation. TKi, YD, TKö: writing—review and editing. All authors have read and approved the final manuscript.

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Declarations

Competing Interests The authors declare no competing interests.

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