Urban Forestry & Urban Greening 118 (2026) 129348

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Patterns of urban green cover and green volume depend on land ownership in Munich, Germany

Xia Yao [a,*], Fabio S.T. Sweet [a], Tobias Leichtle [b], Hannes Taubenböck [b], Stephan Pauleit [c], Wolfgang W. Weisser [a]

[a] Terrestrial Ecology Research Group, Department for Life Science Systems. TUM School of Life Sciences, Technical University of Munich, Freising 85354, Germany
[b] German Aerospace Center, German Remote Sensing Data Center, Oberpfaffenhofen 82234, Germany
[c] Chair for Strategic Landscape Planning and Management, School of Life Sciences, Technical University of Munich, Freising 85354, Germany

ARTICLE INFO

Keywords:
Green space
Green volume
Inequality
Urban nature
Land ownership

ABSTRACT

Green space contributes to human well-being; however, it is often unequally distributed within a city. Here, we focused on the role of land ownership and examined the distribution of vegetation, i.e., urban green, in private and public areas in different urban land use categories in Munich, Germany. We compared green cover to green volume, i.e., 3D greenspace, using a novel high-resolution dataset. We found that green cover was more equally distributed than green volume in grid cells of 100 m x 100 m, as evidenced by consistently lower Gini coefficients for green cover compared to green volume across ownerships. Importantly, green volume was mostly provided by public land, especially parks, urban forests, and semi-natural areas. Low green volume was found in residential and industrial areas, even though green cover was also high in some of these cells. In total, the fraction of area that was green was higher for private areas than public areas in 52.7 % of all grid cells. For green volume, the fraction that was green was higher in public areas in more than 80 % of grid cells, except for those grid cells with very small overall green volume. In grid cells with little green volume, i.e., in cells with a general deficit of greening, public areas did not compensate for low values of vegetation in private areas. Because green volume is more closely related to the provisioning of many ecosystem services than green cover, there is a need to plant higher vegetation, such as trees or bushes. Our analysis shows that it is in particular the private land owners that need to be activated to increase green volume. This will not only increase the overall green volume in the city, but it will also reduce the green volume inequality in the city, in particular in areas where people live and work.

1. Introduction

Urban green spaces are areas characterized by the presence of vegetation (urban green) that provides diverse ecosystem services to humans (Bratman et al., 2019; Fisher et al., 2017; World Health Organization Regional Office for Europe, 2016). These result in substantial benefits to citizens' health and well-being through multiple pathways (Jabbar et al., 2022; Remme et al., 2021). For instance, green spaces provide critical climate regulation ecosystem services by localized thermal amelioration through shading and evapotranspiration, thereby reducing heat-related health risks for urban populations (Kumar et al., 2024; Masoudi et al., 2021; Massaro et al., 2023; Shi et al., 2020). Green spaces also attenuate noise pollution (De Carvalho and Szlafsztein, 2019; Van Renterghem, 2019) and improve sleep quality (Zhang et al., 2024). Additionally, green spaces function as significant sources of cultural ecosystem services that strengthen social cohesion of communities (Jennings and Bamkole, 2019), through mechanisms including the development of place attachment and enhancement of residents' sense of belonging (Hartig et al., 2014), coupled with improvements in perceived neighborhood safety and security (Maas et al., 2009). These multifaceted benefits underscore the importance of systematic green space research for sustainable urban development.

The UN Sustainable Development Goal 11 (United Nations, 2020) aims to "*Make cities and human settlements inclusive, safe, resilient and sustainable*". With respect to urban green space, a target is to "*provide universal access to safe, inclusive and accessible, green and public spaces*" by 2030, with particular emphasis on serving vulnerable populations, including women, children, elderly persons, and individuals with disabilities (United Nations, 2020). However, while all cities have green spaces, the physical amount of vegetation has often been shown to differ

* Correspondence to: TUM School of Life Sciences, Technical University of Munich, Hans-Carl-von-Carlowitz-Platz 2, Freising D-85354, Germany.
E-mail address: xia.yao@tum.de (X. Yao).

https://doi.org/10.1016/j.ufug.2026.129348
Received 25 June 2025; Received in revised form 11 February 2026; Accepted 11 February 2026
Available online 13 February 2026

between different urban areas within the same city (Kabisch et al., 2016). For example, Koprowska et al. (2020) found that the central zone of Lodz, Poland, was covered by a lower percentage of parks and forests, while the majority of bigger parks and/or forests were outside of this area, which resulted in an unequal distribution of public green spaces in Lodz. Similar findings have been made in other studies, that measured e.g. green cover, i.e. the amount of land covered by vegetation (Kabisch et al., 2016; Xu et al., 2018), tree canopy cover (Koh et al., 2022; Leichtle et al., 2021), or the distribution of the Normalized Difference Vegetation Index (NDVI) within cities (Singh, 2018). Thus, green space in cities is often unevenly distributed, but this does not necessarily imply that access to green space is also unevenly distributed.

The issue of access to green space is not just about its spatial distribution; it is also connected to land ownership within urban areas. In general, public green spaces, including parks, urban forests, green corridors, and wilderness areas (Mulatu et al., 2025; Weigand et al., 2023), are characterized by open public access and are managed through hierarchical planning and administrative systems implemented by municipal authorities (Kendal et al., 2012). Conversely, green spaces on private land are generally not open to the public, and include, among others, private gardens, courtyards, corporate landscapes, restricted-access recreational areas, and agricultural lands (Weigand et al., 2023). The management of these spaces is largely determined by landowner preferences and circumstances (Grove et al., 2006; Smith et al., 2005; Weigand et al., 2023). Thus, green spaces that are private and where few people have access are likely to provide fewer services to the general public than a similar area of green space that is on public land. Analyzing green space availability should therefore take into account whether a particular urban green space is private or public.

One particular challenge in assessing green space availability in cities is to obtain reliable data with high spatial resolution. Studies on green space availability use a variety of indicators, but focus mainly on 2-dimensional (2D) representations of green space (Giannico et al., 2022; Su et al., 2025), e.g. green area (Kabisch et al., 2016; Xu et al., 2018) and tree canopy cover (Koh et al., 2022), or more generally, *green cover*. More recently, street view greenness, based on eye-level green (Bai et al., 2024; Wang et al., 2022), has been extracted from street view images based on open-source data and used to measure what is referred to as 2.5-dimensional (2.5D) green, expressed as the Green View Index (GVI). However, while GVI captures more than the area that is green, it does not really represent the full 3D structure of urban green (Jin et al., 2023), which is defined as "the aboveground volume of all plants within a given surface area" (Meinel and Schumacher, 2010; Schmidt and Lawrence, 2022). Obtaining a true 3D representation of this *green volume* has been challenging since it requires detailed vegetation height data. The application of Light Detection And Ranging (LiDAR), has, however, made capturing 3D vegetation data generally possible (Hu et al., 2022; Leichtle et al., 2021). Generally speaking, green volume can be calculated by multiplying the crown area by the height of plants extracted from airborne LiDAR data (Zhou et al., 2022) and high-resolution remote sensing images (Hong et al., 2023), using a number of approaches (Hong et al., 2023, 2025; Huang et al., 2013; Zhou et al., 2022).

Measuring green volume is important as many ecosystem services are closely related to the total amount of vegetation. Consequently, 3D measures of green have proven successful in predicting ecosystem services. For example, green volume provided better predictions for human health outcomes than traditional two-dimensional vegetation indices (Spano et al., 2023). Crown volume and height (Rey-Gozalo et al., 2023; Zhao et al., 2021), along with tree size metrics (Chen et al., 2024), showed stronger correlations with noise reduction capacity than the NDVI (Rey-Gozalo et al., 2023). Furthermore, leaf volume has been shown to exhibit stronger correlations with vegetation evapotranspiration (Kong et al., 2016). Finally, humans intuitively understand green space to be 3-dimensional (Anderson et al., 2018; Xia et al., 2023). Therefore, the assessment of green space availability should enter the 3-dimensional era, allowing for a more comprehensive understanding of green spaces. One key question in this context is whether the distribution of green volume in cities aligns with the patterns of urban green cover that have been analyzed in previous research.

Finally, the amount and configuration of green space have been shown to depend on urban morphology, or, more generally, on land use in cities. This is because different land use categories have specific functional requirements, resulting in different opportunities and limitations for green space (Łaszkiewicz et al., 2022; Li et al., 2015; Masoudi et al., 2021; Raciti et al., 2014; Wang et al., 2016). For example, industrial land use that generally occurs on private land generally features widely-spaced, low- to medium-rise buildings and extensive road networks with parking and storage areas accommodating heavy vehicles. This morphology severely constrains vegetation development, resulting in fragmented green space patterns. Conversely, residential land use, which is also mostly on private land, is often characterized by larger open spaces between structures, enabling the establishment of more vegetation (Masoudi et al., 2021). On public land, opportunities for greening also depend on land use, e.g., whether an area is a park, a street, or a parking space (Croeser et al., 2022). Thus, the interaction between land ownership and urban green cover, as well as green volume, may be systematically different between urban land use categories.

In this paper, we investigated the effect of land ownership on the distribution of vegetation in the city, a topic that so far has been rarely addressed in the discussion of green space availability. We focused on the vegetation present in the city, because this can be detected using remote sensing approaches, rather than on a wider administrative definition of green space that can also include unvegetated areas. In addition to investigating the distribution of 2D green cover, we also asked if this is different from the distribution of 3D green volume. We used information on green cover and a novel high-resolution dataset of green volume for the city of Munich, Germany, to examine the interaction between green space distribution and land ownership for the city as a whole and for different urban land use categories. Specifically, we addressed the following questions:

(1) What is the spatial distribution of green cover and green volume in the private and public areas of the city, and how does this distribution differ among different urban land use categories?
(2) Is private green, i.e. the vegetation in private areas, correlated to public green, i.e. the vegetation in public areas, within grid cells of 100 m × 100 m?
(3) Is green volume closely correlated to green cover, across the city and within different urban land use categories?
(4) What fraction of private and public land is green and which land ownership contributes more to green cover and volume in the city?

2. Materials and methods

The workflow of the analysis is illustrated in Fig. A2 and described in more detail in the following sections. First, we pre-processed essential data sets from remote sensing, including very-high spatial resolution (VHR) imagery, normalized digital surface model (nDSM), CORINE Land Cover (CLC) map, and the Urban Atlas. Second, we calculated the availability of public and private green cover and volume for the entire study area, as well as for different land uses. Finally, we compared the spatial distribution of public and private green cover and volume, explored their relationships, and calculated their contribution to overall green.

2.1. Study area

We conducted this study in Munich (Supplementary material, Fig. A1) because high-resolution data on green volume was available for the city (Leichtle et al., 2021) and because it represents a typical historic, large Central European city. Munich is the capital of the German state of Bavaria, located in the south of Germany close to the Alps (48° 80 130' N, 11° 240 310' E). Munich is the third largest city in Germany after Berlin and Hamburg, with a population of more than 1.5 million (2022), a size of 311 km^2, and a population density of 4842 people/km^2 (LHM München, 2024). Although Munich has a high population density, there is still 74 m^2 of green space per dweller (Hossu et al., 2024; Taubenböck et al., 2021), because it possesses a number of public open green areas (Taubenböck et al., 2021) and private green areas (i.e., agricultural areas and gardens) (LHM München, 2024; Neumann et al., 2024).

2.2. Datasets and preprocessing

Very-high spatial resolution (VHR) imagery of WorldView-3 provided by European Space Imaging (EUSI, www.euspaceimaging.com) was acquired on 2019.07.04 with a spatial resolution of 30 × 30 cm^2. This data served as the basis for the detailed classification of land cover in Munich in an object-based image analysis procedure (Taubenböck et al., 2010; Wurm et al., 2011). Green cover availability was derived from this classification by summarizing all vegetated classes (i.e., grassland, tree cover, etc.). In addition, a VHR normalized digital surface model (nDSM) derived from photogrammetry corresponding to the summer season of 2017 was provided by the city of Munich. The information on green cover was combined with the nDSM in order to calculate the green volume availability with a spatial resolution of 50 × 50 cm^2 (Leichtle et al., 2021). To keep the same spatial resolution as other data, the availability of green cover and green volume in each grid cell of 50 × 50 cm^2 was resampled into 100 × 100 m^2.

The urban land use categories, *Urban green spaces*, *Green semi-natural areas*, *Residential areas*, and *Industrial areas*, are closely related to human living (Abdullahi et al., 2018), work (Chapple, 2014), and leisure (Florindo et al., 2017), hence, we focused our analysis on these key land use categories. For Munich, we constructed these broad land use categories by agglomerating existing more specific land use categories from the CORINE Land Cover (CLC) product. We acquired the most recent data from 2018 from the Copernicus Land Monitoring Service (CLMS) (https://land.copernicus.eu/en) (European Environment Agency, 2020). The land use categories used in this paper were constructed by combining the CORINE categories as follows: "*Green urban areas*" (primarily parks) and "*Sports and leisure facilities*" were combined into "***Urban Green Space***"; "*Broad-leaved forest*", "*Coniferous forest*", "*Mixed forest*", "*Natural grasslands*", and "*Transitional woodland-shrub*" were combined into "***Green semi-natural areas***"; "*Continuous urban fabric*" and "*Discontinuous urban fabric*" were combined into "***Residential areas***"; and "*Airports*", "*Mineral extraction sites*", "*Dump sites*" and "*Industrial or commercial units*" were combined into "***Industrial areas***". (Supplementary material, Fig. A3 and Table A1.) For examples of what public and private green look like in each of these four main land use categories, see Supplementary material Fig A16-A23, and for specific definitions and illustrated examples of each of the CORINE land cover categories, see the 'Updated CLC illustrated nomenclature guidelines' (Kosztra and György, 2019).

To distinguish public and private green spaces, we estimated the ownership of land to identify public and private green spaces based on the Urban Atlas of 2018 (European Environment Agency, 2021), as data privacy considerations made data on the exact ownership of land inaccessible. The Urban Atlas provides public access to detailed land cover/land use maps for 788 Functional Urban Areas across Europe in 27 categories such as continuous urban fabric, discontinuous dense (medium, low, very low density) urban fabric, green urban areas, forests, sports and leisure facilities, and herbaceous vegetation associations (European Environment Agency, 2021). While the land use categories of CORINE are rather broad and lack local details such as ownership, the detailed land use and cover information of the Urban Atlas has already been used to distinguish public and private green spaces repeatedly (e.g., Feltynowski et al., 2018; Kabisch et al., 2016; Wüstemann et al., 2017). This data also allowed us to identify road space, where street trees constitute a significant part of public urban green. In this study, the Urban Atlas categories "green urban areas", "forests", "sports and leisure facilities", "herbaceous vegetation associations", and "other roads and associated land" were classified as public areas, as they generally belong to the government (Bengston et al., 2004; Liu, 2009). Due to public access restrictions, all other areas were considered private. For example, green spaces around houses and community gardens are usually only accessible to owners or tenants (Rolfe et al., 2023) in a continuous or discontinuous urban fabric. Moreover, arable land (Renger, 1995) and pastures (Robinson et al., 2010) belong to the private sector. Therefore, green spaces on public land were considered public green spaces, while those on private land were considered private green spaces.

The multi-source data sets of green cover and green volume data, the Urban Atlas, and the CORINE Land Cover data were spatially aligned (Fig. A4) and then overlaid to show public and private green in different land use categories.

2.3. Assessment of the availability of green cover and volume

To address research question 1, we used the Lorenz curve and Gini coefficient to assess the inequality of the spatial distribution of private and public green cover and volume. The Lorenz curve provides a graphical representation of a skewed distribution that can be interpreted as inequality (Supplementary material, Fig. A5) (Martin and Conway, 2025). Originally, it was used to measure the distribution of wealth within human populations (Lorenz, 1905), and was then gradually applied to quantify the equality of distribution of other variables (Martin and Conway, 2025). The Gini coefficient is derived from the Lorenz curve (Wildman and Shen, 2014), and is used as a quantitative representation of the area under the Lorenz curve (Ceriani and Verme, 2012; Gini, 1912) (see details in Supplementary material, Fig. A5).

In this study, the green cover and green volume Lorenz curve were defined as a ranked distribution of the cumulative percentage of the grid cell in Munich on the horizontal axis versus the cumulative percentage of the green cover or green volume distributed along the vertical axis. Specifically, the cumulative percentage of the total green cover or green volume (y) that is cumulatively shared by x% of the grid cells was graphed. The Gini coefficient can also be expressed as:

$$Gini = 1 - \sum_{k=1}^{n} (A_k - A_{k-1})(G_k + G_{k-1}) \tag{1}$$

In the expression, n is the number of grid cells; A_k is the cumulative proportion of grid cells from grid 1 to grid k, and G_k is the corresponding cumulative proportion of cover or green volume for grid cells 1 to k.

2.4. Relationship between urban green variables

To address research questions 2 and 3, we used Kendall's Tau rank correlation to measure the association between urban green variables. This measure is suitable for assessing the level of dependence of zero-inflated random variables (Kendall, 1938). Correlation analyses were conducted at two levels and addressed two distinct objectives. First, to examine the relationship between public and private green (research question 2), we tested the associations between public green cover and private green cover, as well as between public green volume and private green volume, at the city-wide level. We then performed the same analyses stratified by land-use category, including *Urban Green Space*, *Green semi-natural Areas*, *Residential Areas*, and *Industrial Areas*, to explore whether these relationships varied across different urban morphologies. Second, to assess the associations between green cover and green volume (research question 3), we tested the correlations between total, public, and private green cover, and their corresponding green volume metrics across the entire study area. We then repeated these analyses stratified by the same land-use categories to determine whether the cover-volume relationships differed across urban morphologies.

2.5. Analysis of the fraction of green space that is private or public

To address research question 4, we calculated several metrics for each grid cell: a) total public area and total private area, b) total green cover and total green volume separately for the public areas and for private areas. From these calculations, we could determine the fraction of green cover and volume attributable to public versus private areas in each grid cell that contained greenery.

We defined the fraction of green for each ownership as follows (see Fig. 1):

$$F_1 = \frac{Public\ green\ cover}{Public\ area} \tag{2}$$

where F_1 is the fraction of the public area that is green.

$$F_2 = \frac{Private\ green\ cover}{Private\ area} \tag{3}$$

where F_2 is the fraction of the private area that is green.

For green volume, because the maximum observed green volume in 10,000 m^2 grid cells was 259,480 m^3, we set the maximum height of each grid cell to 25.95 m.

$$Public\ volume = Public\ area\ \times 25.95m \tag{4}$$

$$Private\ volume\ = Private\ area \times 25.95m(5)$$

$$F_3 = \frac{Public\ green\ volume}{Public\ volume} \tag{6}$$

where F_3 is the fraction of the public volume that is green.

$$F_4 = \frac{Private\ green\ volume}{Private\ volume} \tag{7}$$

where F_4 is the fraction of the private volume that is green.

These fractions of land owned by either type of ownership in a grid cell that was green can be considered as the 'relative contribution' to green. For example, if 60 % of the available public area were green space, and 20 % of the available private area were green space, the 'contribution' of the public area to green would be three times that of the 'contribution' of private owners. Note that this calculation is independent of the absolute amount of green space in an area, and does not represent the contribution of the private or public areas to the total amount of green in a cell, but the fraction of each area that is greened. We compared the contributions of public and private areas for grid cells with different levels of green (see Table A2 and A5).

To compare the relative contributions into green, we derived the following quantities: For green cover, we defined C_1 and C_2, depending on whether the fraction of green was higher in private land (F_2>F_1) or public land (F_1>F_2). This ratio of 'relative contribution' into green, therefore, ranges from 0 to 1. Thus,

$$C_1 = \frac{F_1}{F_2} \quad (F_2 > F_1, \quad F_2 \neq 0) \tag{8}$$

where C_1 is the public relative contribution to green cover divided by private contribution, given that the private relative contribution is higher.

$$C_2 = \frac{F_2}{F_1} \quad (F_1 > F_2, \quad F_1 \neq 0) \tag{9}$$

where C_2 is the private relative contribution to green cover divided by the public contribution, given that the public relative contribution is higher.

Similarly, we defined C_3 and C_4:

$$C_3 = \frac{F_3}{F_4} \quad (F_4 > F_3, P_4 \neq 0) \tag{10}$$

when the private relative contribution to green volume is higher, and

$$C_4 = \frac{F_4}{F_3} \quad (F_3 > F_4, \quad F_3 \neq 0) \tag{11}$$

when the public relative contribution is higher.

Examples of grid cells with different public and private contributions to green can be found in the supplementary material, Figs. A14-A23.

In order to be able to make comparisons in situations where either form of ownership did not contain any green at all in the grid cell, we set the grid cells where public or private areas were 0 m^2 to an arbitrary very small value, 1.0×10^{-8} m^2.

3. Results

3.1. Availability and spatial distribution of green cover and green volume in Munich

In response to research question 1, we examined green space availability at three levels: city-wide totals, public and private areas across the city, and within different land use categories.

3.1.1. Availability of green cover and green volume in Munich

Across Munich, there was an average green cover of 5949

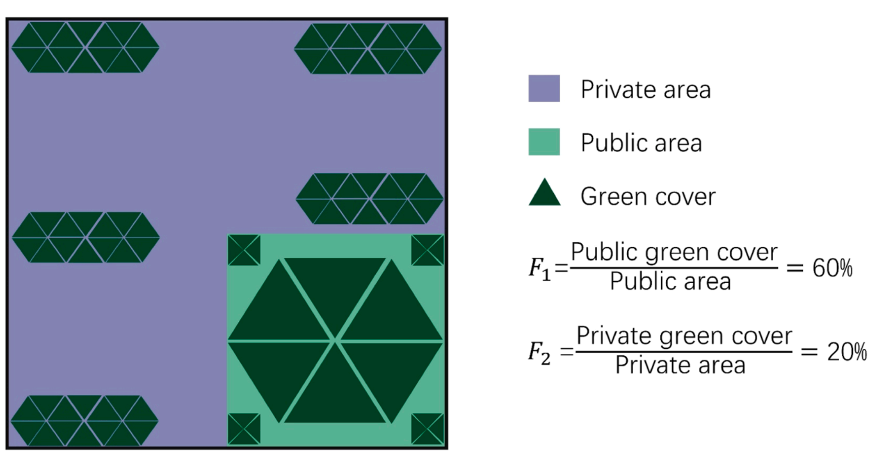

Fig. 1. Schematic visualisation of a single grid cell where the private area makes up 75 % of the total area, and where the fraction of area that is green is higher in the public than in the private area, i.e. the contribution to green is higher public than for private ownership. The colour scheme corresponds to Fig. 4, A2, A10, A13, A15.

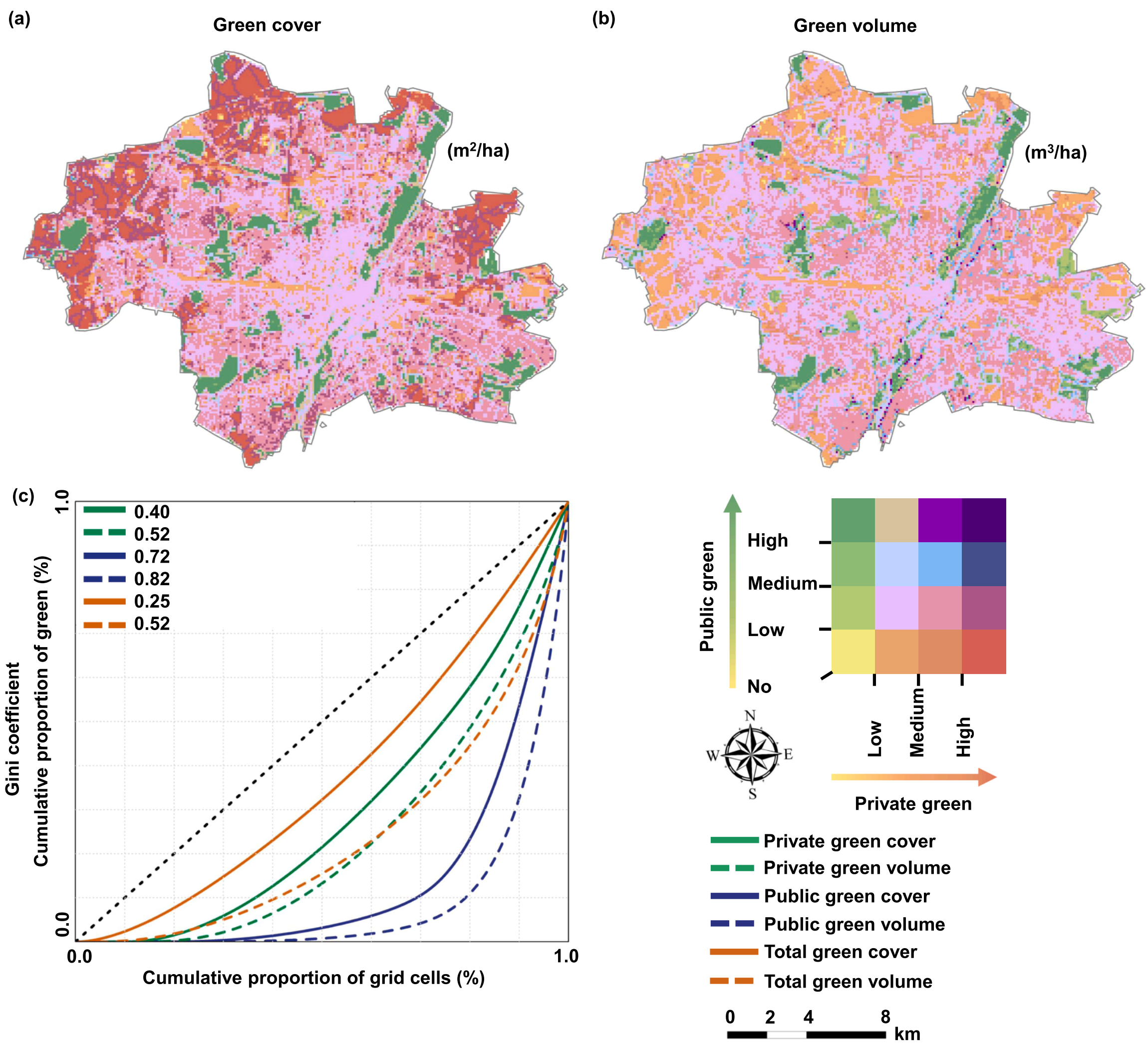

Fig. 2. Spatial availability, Lorenz curve, and Gini coefficient of public, private, and total green cover and volume for the entire city of Munich. (a): green cover, (b): green volume, (c): Lorenz curve and Gini coefficient for green cover and volume. "Bivariate Colors" was utilized for coloring public and private green for both green cover and volume simultaneously. The "Geometric Interval" classification method was adopted to classify the availability of public, private, and total green cover and green volume in Munich into four classes, labelled as "no green" (green cover: value≤0 m^2, green volume: value≤0 m^3), "low" (green cover: 0 <value≤4097 m^2, green volume: 0 <value≤20,590 m^3), "medium" (green cover: 4097 <value≤5921 m^2, green volume: 20,590 <value≤81,180 m^3), and "high" (green cover: value>5921 m^2, green volume: value>81,180 m^3). For results of alternative classifications, see the Supplementary material (Fig. A24). Note that for all calculations in this paper including the Gini coefficient, we use the raw data rather than these categories; these categories exist purely for visualisation purposes.

± 2546 m^2/ha in 30,546 1 ha grid cells. Of this, 31.2 % (57 million m^2) was public green cover, and twice as much, 68.8 % (125 million m^2), was private (Fig. 2, supplementary material Fig. A6). There were only 84 grid cells (0.3 %) without any green cover. For green volume, the average volume was 31,403 ± 34,525 m^3/ha in the 30,546 1 ha grid cells. Of this green volume, 51.9 % (498 million m^3) was public green, and 48.1 % (461 million m^3) was on private land (Fig. A6), i.e., in contrast to the green cover, green volume was found to be roughly equally distributed between public and private areas. 140 grid cells (0.5 %) had no green volume at all, as no green heights were identified in these grid cells, despite the higher green cover in them, such as *Non-irrigated arable land*, and *Sport and leisure facilities*. The Gini coefficient showed a comparatively high spatial equality for green cover, while for total green volume a significant disparity was identified, i.e. green volume was more unevenly distributed between public and private land than green cover (Fig. 2, supplementary material Table A3).

3.1.2. Spatial distribution of private and public green in Munich

Visualization showed public green cover was spatially concentrated in Munich (Fig. 2). Notably, 18.3 % of grid cells had no public green at all (Table A4). Public green volume followed a similar spatial distribution as public green cover, and large public green volumes were generally found where there was a large amount of public green cover (Fig. A6).

Private green cover also showed spatial concentration, but private green volume was generally distributed across many cells (Fig. 2, supplementary material Fig. A6). Only 2872 grid cells (9.4 %) contained no private green space (Table A4). Private green volume was distributed broadly across the city (Fig. 2), and only 9.6 % of the grid cells had no private green volume.

Across the city, the Gini coefficient for total green cover was smaller than for total green volume, even though both total green cover and total green volume followed a similar spatial distribution (Fig. 2, Table A3). The difference in distribution is due to the three-dimensional structure of green volume, because vegetation height varied between different green spaces. This pattern that the Gini coefficient was smaller for green cover than green volume was also true when public and private green cover and volume were considered separately (Fig. 2, supplemental material, Fig. A6).

3.1.3. Distribution of private and public green in different urban land use categories

Fig. A7 (columns 1–4) showed the distribution of private and public green cover and green volume in the main land use categories in Munich. Public green was dominant in grid cells classified as *Urban green space* or *Green semi-natural areas*. Private green was dominant in *Residential areas* and *Industrial areas*. For all land use categories, green cover was more equally distributed than green volume, i.e. the Gini-coefficient was smaller for green cover. However, there were differences in the distributions between public and private green spaces across different land use categories. For *Urban green spaces* and *Green semi-natural areas*, the distribution of public green was more equal than that of private green spaces. The opposite was true for *Residential areas* and *Industrial areas*. While all land use categories thus showed a significant disparity in spatial distribution, the distribution in *Residential areas* was relatively more equal than in the other land use categories.

3.2. Relationship between public and private green in Munich

Regarding research question 2, we examined the relationship between public and private green space at the city-wide level and within different land use categories. The total amount of public green cover in a grid cell was moderately negatively related to the amount of private green cover in the same cell ($r_\tau = -0.42$, $p < 0.05$; supplementary material, Fig. A8). This is because there were many grid cells (27.6 %) with low public and private green cover (Fig. A6), while no grid cell had high shares of both public and private green cover. For green volume, there was also a significant, but very weak, negative correlation between public and private green ($r_\tau = -0.06, p < 0.05$; supplementary material, Fig. A8).

When the main land use categories were considered separately, the correlations between public and private green cover stayed negative, but differed among land use categories. For *Urban green space* ($r_\tau = -0.60$, $p < 0.05$) and *Green semi-natural areas* ($r_\tau = -0.65$, $p < 0.05$), strong negative correlations existed between private and public green cover. In both land use categories, there were many grid cells with high shares of public green cover and low shares of private green cover. These represent the parks such as the English garden, public sports grounds, as well as the forest and grassland. For green volume, these correlations were lower (*Urban green space* ($r_\tau = -0.18$, $p < 0.05$) and *Green semi-natural areas* ($r_\tau = -0.43$, $p < 0.05$)), as there were many grid cells with medium or high public green volume and low private green volume, like parks and forests (Supplementary material, Fig. A8).

For *Residential areas* and *Industrial areas*, correlations between private and public green were generally much weaker, both for cover and for volume (Fig. A8). In *Residential areas*, the correlation between public and private green cover was r_τ = -0.24 ($p < 0.05$), and r_τ = -0.02 ($p < 0.05$) for green volume. There were many grid cells with medium or high values for private green cover, but low public green cover, in particular in the dominant *Discontinuous urban fabric*. In the case of green volume, both public and private areas did not reach high values (Supplementary material, Fig. A8). In *Industrial areas*, the correlation between public and private green cover was $r_\tau = 0.01$ ($p = 0.31$), and $r_\tau = 0.16$ ($p < 0.05$) for green volume – the correlation for green volume was weakly positive. The amount of green was generally low, both when cover and when volume was considered. Many grid cells showed high private green cover but low public green cover. There were very few cells with high public or private green volume, while most grid cells had low public and low private green volume (Supplementary material, Fig. A8).

3.3. Correlation between green cover and green volume

Our analysis showed that the distribution of green cover and green volume differed between land use categories. To answer research question 3 and to understand why the distributions are not the same, we analyzed the correlation between green cover and volume (Fig. 3). Over the entire city, there was a weak positive correlation between the two. When green was partitioned into private and public green, the correlation of green cover and volume was moderately positive in private green, while for public green the correlation was almost three times as strong (Fig. 3). These patterns became clearer when the individual land use categories were considered separately. Strong positive correlations between cover and volume were found generally for *Industrial areas* and *Residential areas*, both when private and public green were considered alone, but also when they were considered together. In contrast, for *Urban green space* and *Green semi-natural areas* correlations were low when both ownerships were considered together. In contrast, the correlation between cover and volume was much higher when private and public areas were considered individually (Fig. 3). The separation into even finer land-use classes explains these patterns: in urban green areas the mixture of grid cells dominated by forests (high volume) and those dominated by grasslands (low volume) breaks the correlation between green cover and volume. Public areas encompass both parks and open areas with grass or meadows, including lawns. For *Urban green spaces*, most grid cells of *Sport and leisure facilities* showed low green volume, whether the green cover was high or low, because of the dominance of lawn in this land use. In *Residential areas* and *Industrial areas*, there are also many grid cells with high (private) green cover but low green volume, in particular in *Discontinuous urban fabric* and *Industrial or commercial units*.

3.4. Relative contribution to green in private and public lands

To understand whether public or private ownership resulted in a proportionally higher fraction of area being green, we calculated the fractions of green in the public or private areas, i.e. the contributions to green, for each grid cell (Research question 4, Table 1, Supplementary materials, Fig. A9). Green cover and green volume showed different patterns. Across Munich, for green cover, the fraction of property that was green was higher for private than for public areas in nearly half of the grid cells (52.7 %) (Table 1). Only 12.3 % of grid cells showed more or less equal fractions of green in public and private areas. In contrast, for green volume, the contribution to green was similar in private and public areas in almost half of the grid cells (47.3 %). For the different land use categories, there were different patterns. In *Urban green space* and *Green semi-natural areas*, most grid cells showed a high fraction of the public land being green when green cover is considered. In contrast, in both *Residential areas* and *Industrial areas*, the fraction of area that is green was higher for private areas. This pattern changed when green volume was considered: across all land use categories, the vast majority of cells showed a much higher fraction of green in public land than in private land, and this was most pronounced in *Residential areas* and *Industrial areas*. This emphasizes that the vegetation on private land is generally not very high, resulting in low volume values.

When comparing the fractions of public and private areas that are green along a gradient in overall greenness of the cells, interesting patterns emerged (Fig. 4, supplementary material, Table A5). In cells with little overall green, there were many cells where the fraction of area that was green was similar for private and public areas, for both green cover and volume (yellow cells in Fig. A10, yellow part of bars in Fig. 4a). In contrast, as the greenness of the cells increased, more and more cells showed higher contributions of green in public land, and this was particularly true for green volume (right-hand sides of each graph in Fig. 4b and Fig. A10 b and d). For green volume, this was true across all land use categories. Thus, in cells with a lot of green volume, the high green volume was mainly due to public contribution to green. This pattern holds broadly across the study area, with public areas contributing more to green volume in over 80 % of grid cells (Fig. 4b, Fig. A10 b, d, and Table A5), with the notable exception of areas with very little overall greening volume.

There were marked differences among the land use categories, in

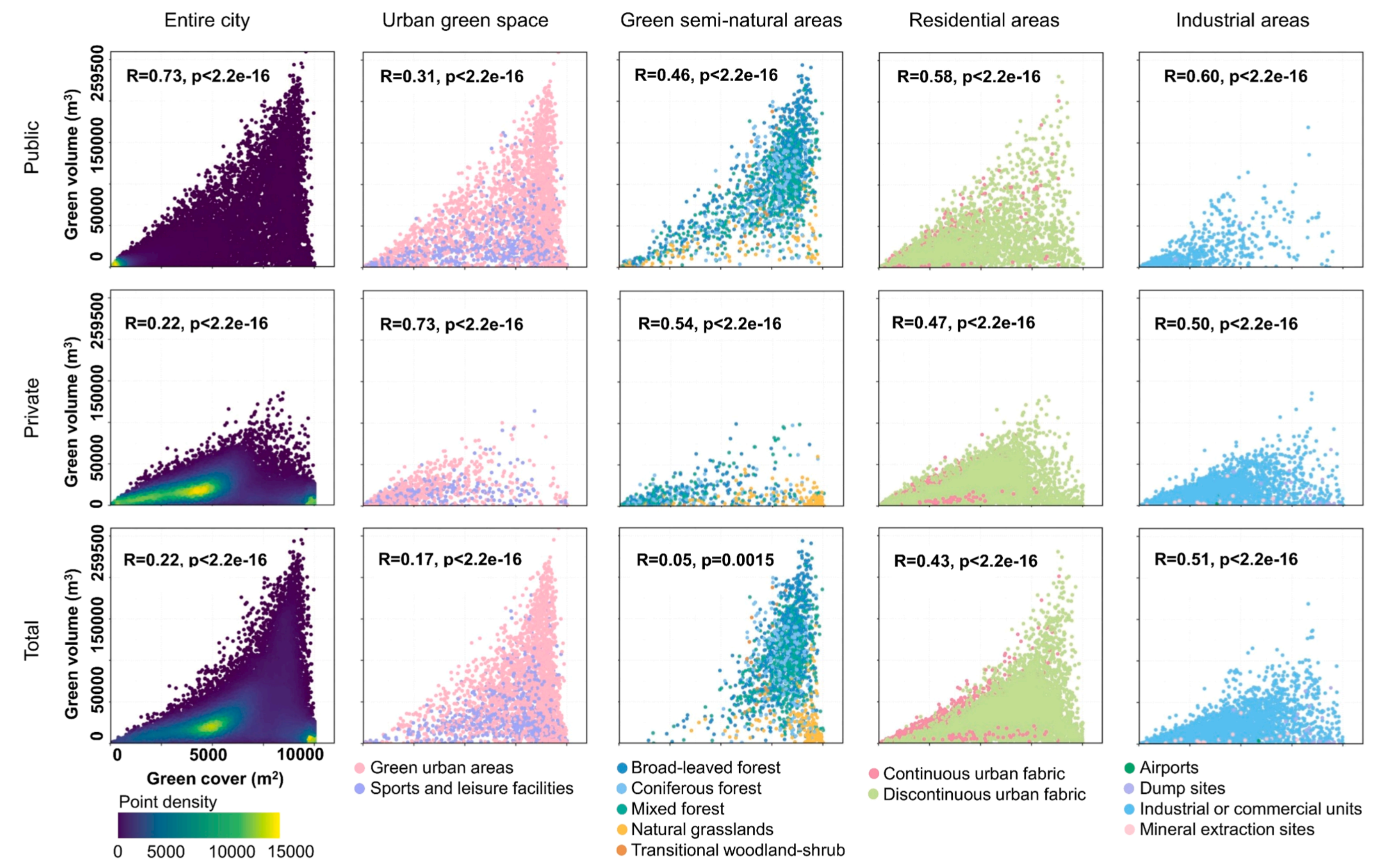

Fig. 3. Correlations between green cover and green volume for the entire city (first column) and different land use categories (columns 2–5). Correlations were done for cells with public green (first row), private green (second row), and total green (sum of private and public green per cell). Correlation analysis was based on ranks (Kendall's Tau), and cells with 0 green were removed for each individual analysis.

Table 1
The percentage of grid cells where the public or private fractions of green cover or volume are equal to each other (±5 %) or one of the fractions is larger than the other. The case containing the largest percentage of grid cells for each land use category is indicated in bold.

	Green cover			Green volume		
	Public fraction larger	Equal (±5 %)	Private fraction larger	Public fraction larger	Equal (±5 %)	Private fraction larger
Entire city	34.9 %	12.3 %	**52.7 %**	26.7 %	**47.3 %**	26.0 %
Urban green space	**81.3 %**	7.1 %	11.6 %	**71.3 %**	19.9 %	8.8 %
Green Semi-natural areas	**74.7 %**	6.1 %	19.3 %	**84.7 %**	11.0 %	4.3 %
Residential areas	32.0 %	13.8 %	**54.2 %**	19.2 %	**45.5 %**	35.3 %
Industrial areas	26.4 %	14.4 %	**57.2 %**	12.6 %	**61.6 %**	25.8 %

particular for green cover. In *Urban green space*, the fraction of area that was green was higher in public than private areas. In contrast, in *Green semi-natural areas* the contribution to green cover was often similar in the private and public parts of the cell (large yellow bar in Fig. 4a), while for *Urban green space* the contribution to green cover was much higher in the public area. For green volume, it was the public areas in these land use categories that showed higher contributions to green.

4. Discussion

In this study, we investigated the distribution of private and public green and compared green cover to green volume, for different urban land use categories. Munich was used as a case study because of the availability of high-resolution data on green volume (Leichtle et al., 2021). Previous studies on Munich, for example, identified all trees in the city (Leichtle et al., 2021), and found that green cover was unequally distributed across the city (Xu et al., 2018). Our results go beyond the previous studies by focusing on green volume, i.e. 3D green.

In our study, private green cover occupied about three-quarters of the entire green space, which is consistent with another study in Frankfurt am Main, Germany, that showed that the private sector was responsible for a high percentage of total urban vegetation cover (Narváez Vallejo et al., 2024). Although public areas were only responsible for one-quarter of the entire green cover, half of the total green volume in the city occurred in areas with public ownership. This shows that the distribution of green volume is not the same as green cover. We found that in Munich, similar to studies in other cities (Kabisch et al., 2016), that green space was unequally distributed within the city. Importantly, green volume was more unequally distributed across the city than green cover, emphasizing that these two metrics measure different aspects of urban greenspace. There was generally a low correlation between green cover and green volume, which was stronger within public than in private areas and which also differed among different urban land use categories. This emphasizes that the third dimension of urban green, vegetation height, varies greatly, even between areas with similar green cover, and seems to be strongly influenced by urban land use. For instance, a grid cell with moderate green cover could have either low-growing grass (relatively small

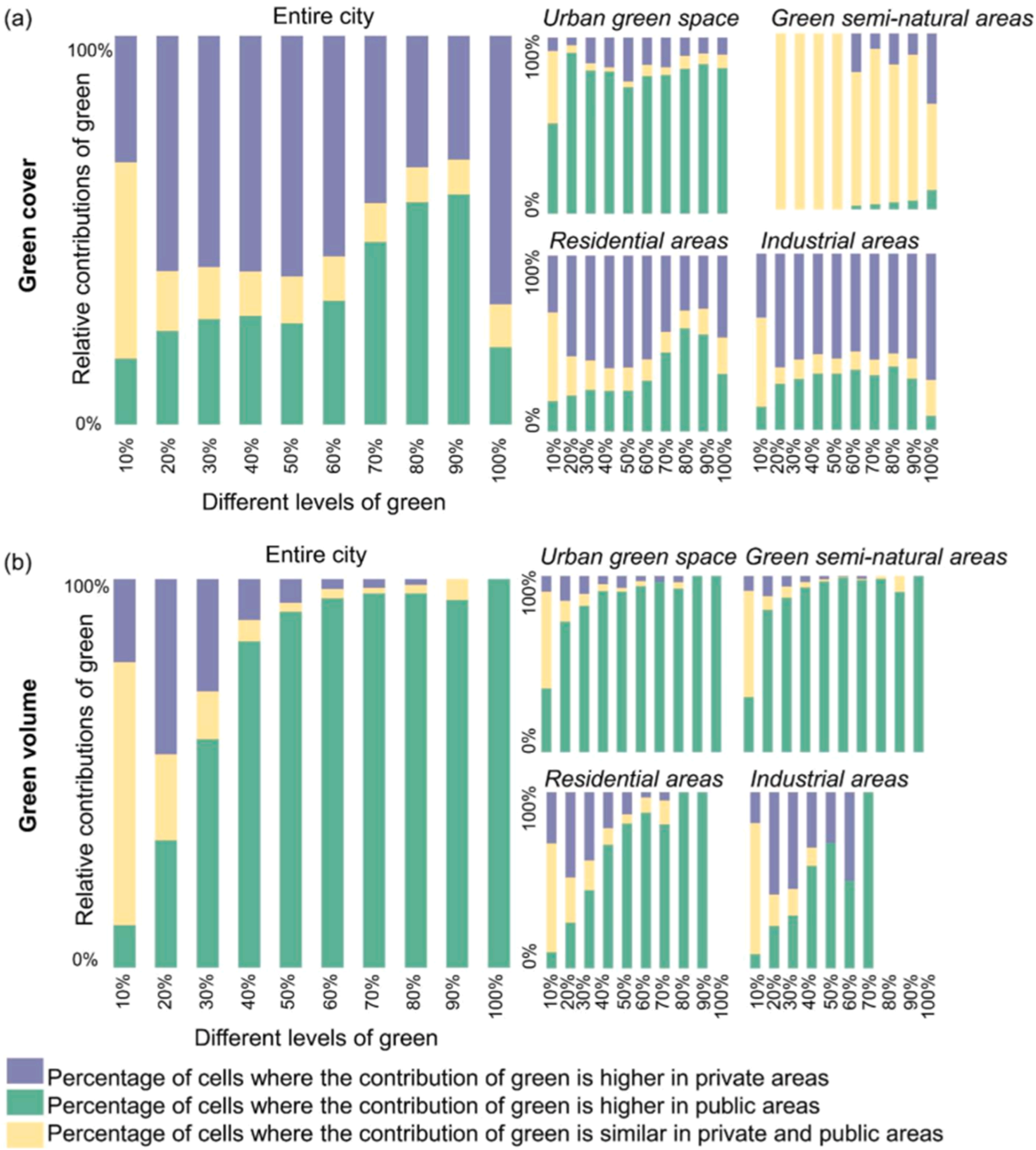

Fig. 4. Relative contributions to green of public and private land as a function of total green in a grid cell, shown separately for different amounts of green in cells (10 % intervals of green). Grid cells where the fraction of land that is green is higher for private than for public land are shown in blue color ($C_1 = \frac{F_1}{F_2}$ ($F_2 > F_1$, $F_2 \neq 0$))), while grid cells for which the fraction of land that is green is higher for public than for private land are shown in green color (($C_2 = \frac{F_2}{F_1}$ ($F_1 > F_2$, $F_1 \neq 0$))). See section 2.5, Eqs. (2)-(11), for a full description of the calculations. (a): green cover, (b): green volume.

volume) or a dense tree canopy (relatively large volume), representing vastly different ecological functions. The weak correlation between green cover and green volume also demonstrates that green volume captures vegetation characteristics that are invisible in 2D cover analysis but crucial for a range of urban ecosystem services that scale with vegetation volume or leaf area. Importantly, in grid cells with overall little green, the fractions of the property that were green were similar for private and public ownership. In contrast, when grid cells were very green, public ownership was associated with a much higher contribution to green, and this was especially true when green volume was considered (Fig. A11 and A12). To summarize, our analysis shows that measures of the distribution of green depend strongly on which measure of green is used, here cover or volume, and that the distribution of green is related to urban land use categories. In the following, we will first discuss the limitations of our study and then the results one by one.

4.1. Limitations

Some uncertainty and limitations in this study should be acknowledged. Accurately identifying public and private areas is a challenge, because land ownership is a privacy issue. In this study, the Urban Atlas was used to separate public and private areas as done in other studies (Feltynowski et al., 2018; Kabisch et al., 2016; Wüstemann et al., 2017), which made it possible to identify public and private lands on a city scale in Munich. However, the mixing of land ownership in some land use classifications might result in a misestimation of public and private areas. For example, it is difficult to disentangle public and private lands in *Continuous and Discontinuous urban fabric*. There are additional difficulties when aligning different urban datasets, for example, the CORINE and green space data do not align perfectly, which also introduces uncertainty for the land use of each grid cell. Unrecognized land use within each area of the grid cell due to unaligned data might result in misidentification of the direct and indirect impacts. Advances in more accurate land use data with higher resolution would be helpful for improving the understanding of urban greening in different land use categories in future studies. Nevertheless, by carefully aligning the different maps we arrived at a workflow that in our view allowed us to correctly answer the questions posed for this paper.

Finally, our measure of green volume is more closely linked to certain ecosystem services, such as cooling (Kong et al., 2016) and noise reduction (Rey-Gozalo et al., 2023), than 2D measures of green as explained above. Nevertheless, this measure still falls short of capturing the full vegetation complexity in urban green spaces. Vegetation complexity is important for biodiversity, as the presence of understory, midstory, and canopy vegetation layers has a fundamental role in the creation of microhabitats and provision of resources for wildlife (Threlfall et al., 2017; Zeng et al., 2023). In principle, measures of vertical and horizontal heterogeneity can be derived from LiDAR data (Heidrich et al., 2020), but such datasets are not yet widely available for many urban areas.

Additionally, the Geometric Interval classification method was employed to categorize green cover and green volume into four classes for visualization purposes (Fig. 2). As the choice of classification method can influence the visual interpretation of spatial patterns in choropleth maps (Brewer and Pickle, 2002; Monmonier, 2018) a sensitivity analysis was conducted comparing four commonly used methods: Geometric Interval, Natural Breaks (Jenks), Equal Interval, and Quantile (Fig. A24, Table A6 and A7). The agreement between Geometric Interval and alternative methods ranged from 72.15 % to 97.21 %, with higher consistency observed for green cover (84.93 %–97.21 %) than for green volume (72.15 %–93.64 %). Visual comparison revealed that the spatial patterns of green cover remained relatively consistent across methods (Fig. A24, a1–d1), while greater visual differences were observed for green volume, particularly with the Quantile method (Fig. A24, d2). These differences can be attributed to how each method responds to skewed data distributions. For private green volume, where high values are rare due to the predominance of low vegetation in private areas, the Geometric Interval, Natural Breaks, and Equal Interval methods produced comparable results, assigning fewer than 1 % of grid cells to the "high" class (0.37 %, 0.16 %, and 0.00 %, respectively). In contrast, the Quantile method, which enforces approximately equal frequencies across classes regardless of the underlying data distribution (Brewer and Pickle, 2002), assigned 10.26 % of grid cells to the "high" class (Table A7). This illustrates that the Quantile method may overrepresent high values when applied to right-skewed data, whereas the other three methods better preserve the distributional characteristics of urban green space. Despite these methodological differences, the core spatial pattern identified in this study, that high green volume is concentrated in public parks and urban forests while private areas exhibit predominantly low green volume, remains consistent across all classification schemes. The Geometric Interval method was ultimately selected because it is specifically designed for right-skewed continuous data (Li and Shan, 2022), providing a balanced representation of both middle and extreme values without compressing the majority of observations into a single class. It should be noted that the categorical labels "low", "medium", and "high" are context-dependent and should be interpreted as relative descriptors. However, it is important to note that this classification affects only the cartographic representation and not the quantitative analyses presented in this study, including the calculations of the Gini coefficients and statistical comparisons, which were based entirely on raw continuous data.

4.2. Private and public areas differ in types of green

Private areas may have smaller trees and a different species composition compared to public areas (Hutt-Taylor and Ziter, 2022; Sousa-Silva et al., 2023). This is probably driven by the limited availability of space for planting trees, as gardens or front yards are generally small (Lin et al., 2017), but also by a lower willingness in private areas to plant trees, due to disservices such as loss of branches, debris, and damage to housing (Roman et al., 2021). Yet the relationship between land ownership and vegetation is spatially complex: private land vegetation is greater in peripheral boroughs, while public street vegetation is highest in select central boroughs and lower in both downtown and peripheral locations (Pham et al., 2012). While evidence from a study suggests that private land may have higher tree species richness and tree abundance than public land (Hutt-Taylor and Ziter, 2022), public green spaces often contain taller vegetation, such as trees (Çoban et al., 2021), and this is also what our data show.

In our study, cells with high values for both green cover and green volume were found predominantly in cells with a high fraction of public ownership (Fig. A6). Thus, even though public green cover only made up about one-quarter of the entire green cover of the city, their volume accounted for about half of the total green volume of Munich. This emphasizes the importance of public green for the provision of ecosystem services as these are often related to the total amount of photosynthetically active surfaces, i.e. the number of leaves present, often expressed as leaf area index (LAI). While public authorities invest significantly in urban tree planting programs (Hilbert et al., 2019), there are significant conflicts about planting trees also in public areas (Sousa-Silva et al., 2023), e.g., due to the potential of damage to urban infrastructure from tree roots, health risks to people from falling branches, and allergen production (Drew-Smythe et al., 2023). As a consequence, cities currently fall short of targets for city greening, e.g., with respect to tree canopy cover (Croeser et al., 2024). Our analysis emphasizes that for a city-wide increase in green volume, private owners need to be activated to plant more trees and other forms of higher vegetation, such as shrubs.

An analysis of the different urban land use categories reinforces this recommendation, but also shows the potential for higher green values in public land. While public areas often contain large trees, in particular in urban parks and forests (Huang et al., 2022; Leichtle et al., 2021; Threlfall et al., 2016), public areas also include grasslands, meadows, and lawns with high green cover but low green volume. Consequently, there is substantial potential for augmenting green volume in these spaces. A large potential for increasing green volume lies in the land use categories *Residential areas* and *Industrial areas*, which are often private. Here, a large proportion of the green cover is lawns and may include some shrubs (Kaya et al., 2018), while trees tend to be young and small (DBH <25 cm) (Hutt-Taylor and Ziter, 2022; Sousa-Silva et al., 2023), resulting in an overall low volume.

4.3. Distribution of private and public green cover and volume

Overall, green cover was more equally distributed across the city than green volume. Private green cover was distributed across many cells, in contrast to more concentrated patterns of public green cover. Thus, if only green cover is considered, private properties play an important role in a more even distribution of green within the city. With respect to accessibility, however, it must be considered that private green areas are unlikely accessible to the general public. In contrast, the significant spatial concentration and overall high inequality in distribution of green volume is not compensated for by private areas, because of the generally low values for green volume in these areas (Fig. A6). This pattern aligns with findings from E. S. Smith et al. (2026), who demonstrated that in English cities, neighbourhood canopy cover was predominantly driven by woodland area proportion rather than private garden tree density, while private garden trees contributed substantially to visual tree access metrics. This differential contribution suggests that private areas, despite containing vegetation that registers in 2-dimensional cover assessments, often lack the mature, structurally complex trees that generate substantial green volume. Thus, 3-dimensional volume metrics capture not merely the presence of trees versus other vegetation types, but also critical structural variation, including tree height, crown depth, and biomass, that 2-dimensional canopy cover cannot distinguish. Future remote sensing products that will not only provide information on green volume, but also structural variation within the vegetation patches, will allow an even more fine-grained analysis of vegetation differences in private and public land and in different land uses.

The fact that most green volume at the city level is provided by public parks and urban forests has been observed repeatedly (e.g., Giannico et al., 2022; Handayani, Estoque, et al., 2018; Handayani et al., 2018). Our analysis shows that increasing green volume in private areas will not only increase the overall green volume in the city, but also has the potential to result in a more even distribution of green volume in the city. Especially in *Industrial areas*, there are significant amounts of green areas with low volume where planting trees is possible to significantly increase green volume.

4.4. Contributions of public and private areas to greening

In addition to analyzing the absolute amounts of green cover and green volume by private and public ownership, we analyzed the contribution to green for private and public areas, i.e., the fraction of the property that was green. While not expressed in monetary values, this fraction can also be considered as 'investment' into green.

Our analysis showed that the fraction of green within private and public property varies considerably between cells and was strongly influenced by urban land use category (Figs. A9, A10). Across the city, only about 12 % of grid cells showed an equal contribution to green in private and public areas for green cover, while for green volume, nearly half of the grid cells had equal contributions of public and private areas into green. Importantly, however, half of the grid cells with more or less equal contributions of the public and private to green cover were in *Discontinuous urban fabric* (Fig. A10 a, c). These grid cells mostly showed intermediate levels of greening. Thus, in these areas where people live and where the private areas were larger than the public areas, the public contributed as much of their property to greening as the (larger) private areas. Almost half of the grid cells in *Discontinuous urban fabric* also showed similar contributions of public and private areas to green volume. Unlike green cover, however, these were cells with overall low green volume, even though the green cover in these cells often exceeded 50 % of the area (Fig. A13). In cells with high overall green volume, this green resulted from high contributions of the public to green, not from the contribution of private landowners (Fig. A10). Finally, in cells with overall low amounts of green volume the contribution of private areas into green volume was often higher than the contributions of public areas, and not the other way round. Taken together this implies that in areas in the city where overall green volume is low, the public sector does not disproportionally green the area by planting trees or other high vegetation. In other word, public greening does not compensate for a lack of green volume in private areas, and this is particularly true in areas such as *Discontinuous urban fabric* where people live.

4.5. Reconciling land ownership and green space accessibility

Our findings reveal a fundamental tension between land ownership patterns and equitable access to green spaces. This tension is part of a broader pattern of distributional inequity observed in present-day cities, where certain urban populations have better access to the benefits of urban green spaces than others (Dai, 2011; Klompmaker et al., 2023; Weigand et al., 2023). While private areas contribute significantly to overall green cover distribution and help to reduce the uneven distribution of green at the city level, the majority of this green space remains inaccessible to the general public (Wolch et al., 2014). Such inaccessibility may further reinforce the so-called "luxury effect," wherein affluent neighborhoods, often characterized by higher housing affordability due to residents' concentration in high-wage employment sectors (Chattopadhyay and Bianchi, 2021; Robinson, 2021), exhibit higher levels of biodiversity and vegetation cover (Aznarez et al., 2023; Hope et al., 2003; C.A. Martin et al., 2004). This creates an "accessibility paradox": areas with more evenly distributed private green cover may appear more equitable from a spatial perspective but functionally remain inequitable due to restricted access.

Several strategies could help reconcile this contradiction: Not all private green spaces are inaccessible (Carmona, 2022; Lee, 2022); semi-public spaces in multi-storey housing areas, owned by private companies or housing associations, yet open to all, exemplify successful integration of private ownership with public access (Amirjani et al., 2025). Expanding this model through public-private partnerships, such as privately owned public spaces (POPS) (Kayden et al., 2000), community gardens (Jennings et al., 2016), and zoning regulations mandating green volume standards could further enhance accessibility. Additionally, targeted public investment in areas with small green volume could compensate for limited private green space accessibility (Rigolon, 2016), while innovative governance approaches such as community stewardship models (Svendsen et al., 2016) or neighborhood-level green space cooperatives could bridge the ownership-accessibility divide while respecting property rights. In addition, initiatives to provide controlled public access to private land, such as the "right to roam" legislation in Scandinavian countries and Scotland (Sandell and Fredman, 2010), conservation easement programs that allow public access while maintaining private ownership (Rissman et al., 2007), and temporary access schemes like "open gardens" events where private yards are opened to the public on designated days (Bhatti et al., 2009), offer promising models for expanding green space accessibility without wholesale land transfer. These strategies acknowledge that achieving universal access to green spaces by urban citizen requires not only a more even spatial distribution of green, but also access to all for the ecosystem services that green spaces provide (Anguelovski, 2014; Jennings et al., 2016).

4.6. Summary and conclusions

Based on multi-modal data sets, i.e., the Urban Atlas, CORINE Land Cover, very high-resolution images, and normalized digital surface models, our study analyzed how urban green is distributed in public and private lands in the city of Munich. Our study is consistent with other studies in that it shows that the distribution of green is not equally distributed within the city as a whole, and within different urban land use categories. Our study goes beyond previous studies by showing that it is mainly the distribution of green volume, a metric more closely related to ecosystem service provision than green cover, that has an unequal distribution and that public land disproportionally contributes to the existing green volume. Our study also shows that private land can play an important role in ensuring a more even distribution of green cover, when public green is concentrated. More importantly, there is an enormous potential for enhancing green volume in private land within the city, as three-quarters of the entire green space is private. Therefore, encouraging private owners to plant more high vegetation, especially in *Residential areas* and *Industrial areas*, would be the next keystone for improving green space inequality.

CRediT authorship contribution statement

Hannes Taubenböck: Writing – review & editing, Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **Tobias Leichtle:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization. **Wolfgang W. Weisser:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Stephan Pauleit:** Writing – review & editing, Resources, Methodology, Funding acquisition. **Sweet Fabio S. T.:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology. **Xia Yao:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

None declared.

Acknowledgments

We would like to thank the project GRK 2679: Urban Green Infrastructure – Scientific Training of Future Experts in Integrated Urban Planning German (NO. 437788427) funded by Research Foundation DFG. We also would like to thank Sebastian T. Meyer, Robin Heinen, and Andrew Fairbairn for the discussion.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2026.129348.

References

Abdullahi, S., Pradhan, B., Mojaddadi, H., 2018. City compactness: assessing the influence of the growth of residential land use (world). J. Urban Technol. https://doi.org/10.1080/10630732.2017.1390299 ⟨https://www.tandfonline.com/doi/abs/⟩ (world).

Amirjani, R., Tabrizi, N., Kashi, S.M.H., 2025. Uncovering key components of semi-public spaces in multi-unit residences for enhancing social sustainability. Sustain. Cities Soc. 121, 106155. https://doi.org/10.1016/j.scs.2025.106155.

Anderson, K., Hancock, S., Casalegno, S., Griffiths, A., Griffiths, D., Sargent, F., McCallum, J., Cox, D.T.C., Gaston, K.J., 2018. Visualising the urban green volume: Exploring LiDAR voxels with tangible technologies and virtual models. Landsc. Urban Plan. 178, 248–260. https://doi.org/10.1016/j.landurbplan.2018.05.024.

Anguelovski, I., 2014. Neighborhood as Refuge Community Reconstruction, Place Remaking, and Environmental Justice in the City. https://doi.org/10.7551/mitpress/9780262026925.001.0001.

Aznarez, C., Svenning, J.C., Pacheco, J.P., Have Kallesøe, F., Baró, F., Pascual, U., 2023. Luxury and legacy effects on urban biodiversity, vegetation cover and ecosystem services. npj Urban Sustain. 3 (1). https://doi.org/10.1038/s42949-023-00128-7.

Bai, Z., Wang, Z., Li, D., Wang, X., Jian, Y., 2024. The relationships between 2D and 3D green index altered by spatial attributes at high spatial resolution. Urban For. Urban Green. 101, 128540. https://doi.org/10.1016/j.ufug.2024.128540.

Bengston, D.N., Fletcher, J.O., Nelson, K.C., 2004. Public policies for managing urban growth and protecting open space: Policy instruments and lessons learned in the United States. In: Landscape and Urban Planning, 69. The Social Aspects of Landscape Change: Protecting Open Space Under the Pressure of Development, pp. 271–286. https://doi.org/10.1016/j.landurbplan.2003.08.007.

Bhatti, M., Church, A., Claremont, A., Stenner, P., 2009. I love being in the garden': enchanting encounters in everyday life. Soc. Cult. Geogr. 10 (1), 61–76. https://doi.org/10.1080/14649360802553202.

Bratman, G.N., Anderson, C.B., Berman, M.G., Cochran, B., de Vries, S., Flanders, J., Folke, C., Frumkin, H., Gross, J.J., Hartig, T., Kahn, P.H., Kuo, M., Lawler, J.J., Levin, P.S., Lindahl, T., Meyer-Lindenberg, A., Mitchell, R., Ouyang, Z., Roe, J., Daily, G.C., 2019. Nature and mental health: an ecosystem service perspective. Sci. Adv. 5 (7), eaax0903. https://doi.org/10.1126/sciadv.aax0903.

Brewer, C.A., Pickle, L., 2002. Evaluation of methods for classifying epidemiological data on choropleth maps in series. Ann. Assoc. Am. Geogr. 92 (4), 662–681. https://doi.org/10.1111/1467-8306.00310.

Carmona, M., 2022. The "public-isation" of private space – towards a charter of public space rights and responsibilities. J. Urban. Int. Res. Place. Urban.Sustain. 15 (2), 133–164. https://doi.org/10.1080/17549175.2021.1887324.

Ceriani, L., Verme, P., 2012. The origins of the Gini index: extracts from Variabilità e Mutabilità (1912) by Corrado Gini. J. Econ. Inequal. 10 (3), 421–443. https://doi.org/10.1007/s10888-011-9188-x.

Chapple, K., 2014. The highest and best use? Urban industrial land and job creation. Econ. Dev. Q. 28 (4), 300–313. https://doi.org/10.1177/0891242413517134.

Chattopadhyay, S., Bianchi, E.C., 2021. Does the black/white wage gap widen during recessions? Work Occup. 48 (3), 247–284. https://doi.org/10.1177/0730888420968148.

Chen, S., He, P., Yu, B., Wei, D., Chen, Y., 2024. The challenge of noise pollution in high-density urban areas: relationship between 2D/3D urban morphology and noise perception. Build. Environ. 253, 111313. https://doi.org/10.1016/j.buildenv.2024.111313.

Çoban, S., Yener, D., Bayraktar, S., 2021. Woody plant composition and diversity of urban green spaces in Istanbul, Turkey. Plant Biosyst. Int. J. Deal. All Asp. Plant Biol. 155 (1), 83–91. https://doi.org/10.1080/11263504.2020.1727980.

Croeser, T., Garrard, G.E., Visintin, C., Kirk, H., Ossola, A., Furlong, C., Clements, R., Butt, A., Taylor, E., Bekessy, S.A., 2022. Finding space for nature in cities: the considerable potential of redundant car parking. Npj Urban Sustain. 2 (1), 27. https://doi.org/10.1038/s42949-022-00073-x.

Croeser, T., Sharma, R., Weisser, W.W., Bekessy, S.A., 2024. Acute canopy deficits in global cities exposed by the 3-30-300 benchmark for urban nature. Nat. Commun. 15 (1), 9333. https://doi.org/10.1038/s41467-024-53402-2.

Dai, D., 2011. Racial/ethnic and socioeconomic disparities in urban green space accessibility: Where to intervene? Landsc. Urban Plan. 102 (4), 234–244. https://doi.org/10.1016/j.landurbplan.2011.05.002.

De Carvalho, R.M., Szlafsztein, C.F., 2019. Urban vegetation loss and ecosystem services: The influence on climate regulation and noise and air pollution. Environ. Pollut. 245, 844–852. https://doi.org/10.1016/j.envpol.2018.10.114.

Drew-Smythe, J.J., Davila, Y.C., McLean, C.M., Hingee, M.C., Murray, M.L., Webb, J.K., Krix, D.W., Murray, B.R., 2023. Community perceptions of ecosystem services and disservices linked to urban tree plantings. Urban For. Urban Green. 82, 127870. https://doi.org/10.1016/j.ufug.2023.127870.

European Environment Agency. (2020). CORINE Land Cover. URL: ⟨https://sdi.eea.europa.eu/catalogue/copernicus/api/records/960998c1-1870-4e82-8051-6485205ebbac⟩. Access Date: 02.09.2024.

European Environment Agency. (2021). Urban Atlas. URL: ⟨https://sdi.eea.europa.eu/catalogue/copernicus/api/records/fb4dffa1-6ceb-4cc0-8372-1ed354c285e6⟩. Access Date: 02.09.2024.

Feltynowski, M., Kronenberg, J., Bergier, T., Kabisch, N., Łaszkiewicz, E., Strohbach, M. W., 2018. Challenges of urban green space management in the face of using inadequate data. Urban For. Urban Green. 31, 56–66. https://doi.org/10.1016/j.ufug.2017.12.003.

Fisher, J.E., Andersen, Z.J., Loft, S., Pedersen, M., 2017. Opportunities and challenges within urban health and sustainable development. In: Current Opinion in Environmental Sustainability, 25. Sustainability Challenges, pp. 77–83. https://doi.org/10.1016/j.cosust.2017.08.008.

Florindo, A.A., Barrozo, L.V., Cabral-Miranda, W., Rodrigues, E.Q., Turrell, G., Goldbaum, M., Cesar, C.L.G., Giles-Corti, B., 2017. Public open spaces and leisure-time walking in brazilian adults. Int. J. Environ. Res. Public Health 14 (6), 553. https://doi.org/10.3390/ijerph14060553.

Giannico, V., Stafoggia, M., Spano, G., Elia, M., Dadvand, P., Sanesi, G., 2022. Characterizing green and gray space exposure for epidemiological studies: Moving from 2D to 3D indicators. Urban For. Urban Green. 72, 127567. https://doi.org/10.1016/j.ufug.2022.127567.

Gini, C., 1912. Variabilità e mutabilità: Contributo allo studio delle distribuzioni e delle relazioni statistiche. Tipogr. di P. Cuppini.

Grove, J.M., Troy, A.R., O'Neil-Dunne, J.P.M., Burch, W.R., Cadenasso, M.L., Pickett, S. T.A., 2006. Characterization of Households and its Implications for the Vegetation of Urban Ecosystems. Ecosystems 9 (4), 578–597. https://doi.org/10.1007/s10021-006-0116-z.

Handayani, H.H., Estoque, R.C., Murayama, Y., 2018. Estimation of built-up and green volume using geospatial techniques: a case study of Surabaya, Indonesia. Sustain. Cities Soc. 37, 581–593. https://doi.org/10.1016/j.scs.2017.10.017.

Handayani, H.H., Murayama, Y., Ranagalage, M., Liu, F., Dissanayake, D., 2018. Geospatial analysis of horizontal and vertical urban expansion using multi-spatial resolution data: a case study of Surabaya, Indonesia. Remote Sens. 10 (10), 1599. https://doi.org/10.3390/rs10101599.

Hartig, T., Mitchell, R., de Vries, S., Frumkin, H., 2014. Nature and health. Annu. Rev. Public Health 35, 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443.

Heidrich, L., Bae, S., Levick, S., Seibold, S., Weisser, W., Krzystek, P., Magdon, P., Nauss, T., Schall, P., Serebryanyk, A., Wöllauer, S., Ammer, C., Bässler, C., Doerfler, I., Fischer, M., Gossner, M.M., Heurich, M., Hothorn, T., Jung, K., Müller, J., 2020. Heterogeneity–diversity relationships differ between and within trophic levels in temperate forests. Nat. Ecol. Evol. 4 (9), 1204–1212. https://doi.org/10.1038/s41559-020-1245-z.

Hilbert, D.R., Roman, L.A., Koeser, A.K., Vogt, J., Doorn, N.S. van, 2019. Urban Tree Mortality: A Literature Review. Arboric. Urban For. (AUF) 45 (5), 167–200. https://doi.org/10.48044/jauf.2019.015.

Hong, Z., Liu, Y., Xu, W., Wang, L., Lu, N., Ou, G., Kou, W., 2025. A new method of three-dimensional green volume retrieval and its applications in urban greenery evaluation. Ecol. Indic. 176, 113629. https://doi.org/10.1016/j.ecolind.2025.113629.

Hong, Z., Xu, W., Liu, Y., Wang, L., Ou, G., Lu, N., Dai, Q., 2023. Retrieval of three-dimensional green volume in urban green space from multi-source remote sensing data. Article 22. Remote Sens. 15 (22). https://doi.org/10.3390/rs15225364.

Hope, D., Gries, C., Zhu, W., Fagan, W.F., Redman, C.L., Grimm, N.B., Nelson, A.L., Martin, C., Kinzig, A., 2003. Socioeconomics drive urban plant diversity. Proc. Natl. Acad. Sci. 100 (15), 8788–8792. https://doi.org/10.1073/pnas.1537557100.

Hossu, C.A., Artmann, M., Saito, T., Van Lierop, M., Ioja, C.I., Pauleit, S., 2024. Understanding residents' engagement for the protection of urban green spaces by enriching the value-belief-norm theory with relational values—A case study of Munich (Germany). People Nat. 6 (4), 1538–1555. https://doi.org/10.1002/pan3.10654.

Hu, T., Wei, D., Su, Y., Wang, X., Zhang, J., Sun, X., Liu, Y., Guo, Q., 2022. Quantifying the shape of urban street trees and evaluating its influence on their aesthetic functions based on mobile lidar data. ISPRS J. Photogramm. Remote Sens. 184, 203–214. https://doi.org/10.1016/j.isprsjprs.2022.01.002.

Huang, R., Tian, Q., Zhang, Y., Wu, Y., Li, Z., Tang, Z., Zhou, A., 2022. Response of leaf functional traits of landscape plants to urban green space environment in Lanzhou, China. Article 5. Forests 13 (5). https://doi.org/10.3390/f13050682.

Huang, Y., Yu, B., Zhou, J., Hu, C., Tan, W., Hu, Z., Wu, J., 2013. Toward automatic estimation of urban green volume using airborne LiDAR data and high resolution Remote Sensing images. Front. Earth Sci. 7 (1), 43–54. https://doi.org/10.1007/s11707-012-0339-6.

Hutt-Taylor, K., Ziter, C.D., 2022. Private trees contribute uniquely to urban forest diversity, structure and service-based traits. Urban For. Urban Green. 78, 127760. https://doi.org/10.1016/j.ufug.2022.127760.

Jabbar, M., Yusoff, M.M., Shafie, A., 2022. Assessing the role of urban green spaces for human well-being: a systematic review. GeoJournal 87 (5), 4405–4423. https://doi.org/10.1007/s10708-021-10474-7.

Jennings, V., Bamkole, O., 2019. The relationship between social cohesion and urban green space: an avenue for Health Promotion. Article 3. Int. J. Environ. Res. Public Health 16 (3). https://doi.org/10.3390/ijerph16030452.

Jennings, V., Larson, L., Yun, J., 2016. Advancing sustainability through urban green space: cultural ecosystem services, equity, and social determinants of health. Int. J. Environ. Res. Public Health 13 (2), 196. https://doi.org/10.3390/ijerph13020196.

Jin, B., Geng, J., Ke, S., Pan, H., 2023. Analysis of spatial variation of street landscape greening and influencing factors: an example from Fuzhou city, China. Sci. Rep. 13 (1), 21767. https://doi.org/10.1038/s41598-023-49308-6.

Kabisch, N., Strohbach, M., Haase, D., Kronenberg, J., 2016. Urban green space availability in European cities. Ecol. Indic. Navig. Urban Complex. Adv. Underst. Urban Soc. Ecol. Syst. Transform. Resil. 70, 586–596. https://doi.org/10.1016/j.ecolind.2016.02.029.

Kaya, L.G., Kaynakci-Elinc, Z., Yucedag, C., Cetin, M., 2018. Environmental outdoor plant preferences: a practical approach for choosing outdoor plants in urban or suburban residential areas in antalya, Turkey⟨https://www.webofscience.com/api/gateway?GWVersion=2&SrcApp=dspace_ku&SrcAuth=WosAPI&KeyUT=WOS:000455562400002&DestLinkType=FullRecord&DestApp=WOS⟩.

Kayden, J.S., Planning, T.N.Y.C.D. of C., York, T.M.A.S. of N., 2000. Privately Owned Public Space: The New York City Experience. John Wiley & Sons.

Kendal, D., Williams, N.S.G., Williams, K.J.H., 2012. Drivers of diversity and tree cover in gardens, parks and streetscapes in an Australian city. Urban For. Urban Green. 11 (3), 257–265. https://doi.org/10.1016/j.ufug.2012.03.005.

Kendall, M.G., 1938. A New Measure of Rank Correlation. Biometrika 30 (1–2), 81–93. https://doi.org/10.1093/biomet/30.1-2.81.

Klompmaker, J.O., Hart, J.E., Bailey, C.R., Browning, M.H.E.M., Casey, J.A., Hanley, J.R., Minson, C.T., Ogletree, S.S., Rigolon, A., Laden, F., James, P., 2023. Racial, Ethnic, and Socioeconomic Disparities in Multiple Measures of Blue and Green Spaces in the United States. Environ. Health Perspect. 131 (1), 17007. https://doi.org/10.1289/EHP11164.

Koh, C., Kondo, M.C., Rollins, H., Bilal, U., 2022. Socioeconomic disparities in hypertension by levels of green space availability: a cross-sectional study in Philadelphia, PA. Int. J. Environ. Res. Public Health 19 (4), 2037. https://doi.org/10.3390/ijerph19042037.

Kong, F., Yan, W., Zheng, G., Yin, H., Cavan, G., Zhan, W., Zhang, N., Cheng, L., 2016. Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation. Agric. For. Meteorol. 217, 22–34. https://doi.org/10.1016/j.agrformet.2015.11.005.

Koprowska, K., Łaszkiewicz, E., Kronenberg, J., 2020. Is urban sprawl linked to green space availability? Ecol. Indic. 108, 105723. https://doi.org/10.1016/j.ecolind.2019.105723.

Kosztra, B., & György, B. (2019). *U*pdated CLC illustrated nomenclature guidelines. ⟨https://land.copernicus.eu/content/corine-land-cover-nomenclature-guidelines/html/⟩.

Kumar, P., Debele, S.E., Khalili, S., Halios, C.H., Sahani, J., Aghamohammadi, N., Andrade, M., de, F., Athanassiadou, M., Bhui, K., Calvillo, N., Cao, S.-J., Coulon, F., Edmondson, J.L., Fletcher, D., Dias de Freitas, E., Guo, H., Hort, M.C., Katti, M., Kjeldsen, T.R., Jones, L., 2024. Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. Innovation 5 (2), 100588. https://doi.org/10.1016/j.xinn.2024.100588.

Łaszkiewicz, E., Wolff, M., Andersson, E., Kronenberg, J., Barton, D.N., Haase, D., Langemeyer, J., Baró, F., McPhearson, T., 2022. Greenery in urban morphology: a comparative analysis of differences in urban green space accessibility for various urban structures across European cities. Ecol. Soc. 27 (3). https://doi.org/10.5751/ES-13453-270322.

Lee, D., 2022. Whose space is privately owned public space? Exclusion, underuse and the lack of knowledge and awareness. Urban Res. Pract. 15 (3), 366–380. https://doi.org/10.1080/17535069.2020.1815828.

Leichtle, T., Zehner, M., Kühnl, M., Martin, K., Taubenböck, H., 2021. Urban Trees – Detection, Delineation, Quantification, and Characterisation based on VHR Remote Sensing. CITIES 20.50 – Creating Habitats for the 3rd Millennium: Smart – Sustainable – Climate Neutral. Proceedings of REAL CORP 2021, 26th International Conference on Urban Development, Regional Planning and Information Society, 1029–1039..

LHM München. (2024). Munich Facts and Figures*,* 2023. URL: ⟨https://stadt.muenchen.de/dam/jcr:25676806-64e1-43b7-8f20-856e11399bd5/LHM_Stat.-Faltkarte_englisch_2023.pdf⟩. Access Date: 07.08.2024.

Li, W., Bai, Y., Zhou, W., Han, C., Han, L., 2015. Land use significantly affects the distribution of urban green space: case study of Shanghai, China. J. Urban Plan. Dev. 141 (3), A4014001. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000246.

Li, S., Shan, J., 2022. Adaptive Geometric Interval Classifier. ISPRS Int. J. GeoInf. 11 (8). https://doi.org/10.3390/ijgi11080430.

Lin, B.B., Gaston, K.J., Fuller, R.A., Wu, D., Bush, R., Shanahan, D.F., 2017. How green is your garden?: Urban form and socio-demographic factors influence yard vegetation, visitation, and ecosystem service benefits. Landsc. Urban Plan. 157, 239–246. https://doi.org/10.1016/j.landurbplan.2016.07.007.

Liu, Y.-D., 2009. Sport and social inclusion: evidence from the performance of public leisure facilities. Soc. Indic. Res. 90 (2), 325–337. https://doi.org/10.1007/s11205-008-9261-4.

Lorenz, M.O., 1905. Methods of measuring the concentration of wealth. Publ. Am. Stat. Assoc. (World). https://doi.org/10.1080/15225437.1905.10503443. ⟨https://www.tandfonline.com/doi/abs/⟩.

Maas, J., Spreeuwenberg, P., van Winsum-Westra, M., Verheij, R.A., Vries, S., Groenewegen, P.P., 2009. Is green space in the living environment associated with people's feelings of social safety? Environ. Plan. A Econ. Space 41 (7), 1763–1777. https://doi.org/10.1068/a4196.

Martin, A.J.F., Conway, T.M., 2025. Using the Gini Index to quantify urban green inequality: a systematic review and recommended reporting standards. Landsc. Urban Plan. 254, 105231. https://doi.org/10.1016/j.landurbplan.2024.105231.

Martin, C.A., Warren, P.S., Kinzig, A.P., 2004. Neighborhood socioeconomic status is a useful predictor of perennial landscape vegetation in residential neighborhoods and embedded small parks of Phoenix, AZ. Landsc. Urban Plan. 69 (4), 355–368.

Masoudi, M., Tan, P.Y., Fadaei, M., 2021. The effects of land use on spatial pattern of urban green spaces and their cooling ability. Urban Clim. 35, 100743. https://doi.org/10.1016/j.uclim.2020.100743.

Massaro, E., Schifanella, R., Piccardo, M., Caporaso, L., Taubenböck, H., Cescatti, A., Duveiller, G., 2023. Spatially-optimized urban greening for reduction of population exposure to land surface temperature extremes. Nat. Commun. 14 (1), 2903. https://doi.org/10.1038/s41467-023-38596-1.

Meinel, G., Schumacher, U., 2010. Flächennutzungsmonitoring II. ⟨https://www2.ioer.de/recherche/pdf/2010_meinel_ioer-schriften_52_183.pdf⟩.

Monmonier, M., 2018. How to Lie with Maps, Third ed. University of Chicago Press ⟨https://press.uchicago.edu/ucp/books/book/chicago/H/bo27400568.html⟩.

Mulatu, T., Larsen, L., Yeshitella, K., 2025. The impact of land governance and ownership regimes on public green spaces in East African cities: the case of Addis Ababa (Ethiopia) and Kampala (Uganda). Cities 156, 105539. https://doi.org/10.1016/j.cities.2024.105539.

Narváez Vallejo, A., Schwarz-v.Raumer, H.-G., Eisenberg, B., 2024. The interplay of land-use and land-ownership as a key for urban greening management. Urban For. Urban Green. 99, 128442. https://doi.org/10.1016/j.ufug.2024.128442.

Neumann, A.E., Conitz, F., Karlebowski, S., Sturm, U., Schmack, J.M., Egerer, M., 2024. Flower richness is key to pollinator abundance: the role of garden features in cities. Basic Appl. Ecol. 79, 102–113. https://doi.org/10.1016/j.baae.2024.06.004.

Pham, T.-T.-H., Apparicio, P., Séguin, A.-M., Landry, S., Gagnon, M., 2012. Spatial distribution of vegetation in Montreal: an uneven distribution or environmental inequity? Landsc. Urban Plan. 107 (3), 214–224. https://doi.org/10.1016/j.landurbplan.2012.06.002.

Raciti, S.M., Hutyra, L.R., Newell, J.D., 2014. Mapping carbon storage in urban trees with multi-source remote sensing data: Relationships between biomass, land use, and demographics in Boston neighborhoods. *500–501* Sci. Total Environ. 72–83. https://doi.org/10.1016/j.scitotenv.2014.08.070.

Remme, R.P., Frumkin, H., Guerry, A.D., King, A.C., Mandle, L., Sarabu, C., Bratman, G.N., Giles-Corti, B., Hamel, P., Han, B., Hicks, J.L., James, P., Lawler, J.J., Lindahl, T., Liu, H., Lu, Y., Oosterbroek, B., Paudel, B., Sallis, J.F., Daily, G.C., 2021. An ecosystem service perspective on urban nature, physical activity, and health. Proc. Natl. Acad. Sci. 118 (22), e2018472118. https://doi.org/10.1073/pnas.2018472118.

Renger, J.M., 1995. Institutional, communal, and individual ownership or possession of arable land in ancient mesopotamia from the end of the fourth to the end of the first Millennium B. C. Chic. Kent. Law Rev. 71, 269.

Rey-Gozalo, G., Barrigón Morillas, J.M., Montes González, D., Vílchez-Gómez, R., 2023. Influence of Green Areas on the Urban Sound Environment. Curr. Pollut. Rep. 9 (4), 746–759. https://doi.org/10.1007/s40726-023-00284-5.

Rigolon, A., 2016. A complex landscape of inequity in access to urban parks: a literature review. Landsc. Urban Plan. 153, 160–169. https://doi.org/10.1016/j.landurbplan.2016.05.017.

Rissman, A.R., Lozier, L., Comendant, T., Kareiva, P., Kiesecker, J.M., Shaw, M.R., Merenlender, A.M., 2007. Conservation easements: biodiversity protection and private use. Conserv. Biol. J. Soc. Conserv. Biol. 21 (3), 709–718. https://doi.org/10.1111/j.1523-1739.2007.00660.x.

Robinson, J.N., I.I.I., 2021. Surviving capitalism: affordability as a racial "Wage" in contemporary housing markets. Soc. Probl. 68 (2), 321–339. https://doi.org/10.1093/socpro/spaa078.

Robinson, S., Whitton, M., Biber-Klemm, S., Muzofirshoev, N., 2010. The impact of land-reform legislation on pasture tenure in Gorno-Badakhshan: from common resource to private property? Mt. Res. Dev. 30 (1), 4–13. https://doi.org/10.1659/MRD-JOURNAL-D-09-00011.1.

Rolfe, S., McKee, K., Feather, J., Simcock, T., Hoolachan, J., 2023. The role of private landlords in making a rented house a home. Int. J. Hous. Policy (World). https://doi.org/10.1080/19491247.2021.2019882. ⟨https://www.tandfonline.com/doi/abs/⟩.

Roman, L.A., Conway, T.M., Eisenman, T.S., Koeser, A.K., Ordóñez Barona, C., Locke, D. H., Jenerette, G.D., Östberg, J., Vogt, J., 2021. Beyond 'trees are good': Disservices, management costs, and tradeoffs in urban forestry. Ambio 50 (3), 615–630. https://doi.org/10.1007/s13280-020-01396-8.

Sandell, K., Fredman, P., 2010. The right of public access – Opportunity or obstacle for nature tourism in Sweden? Scand. J. Hosp. Tour. 10 (3), 291–309. https://doi.org/10.1080/15022250.2010.502366.

Schmidt, P., Lawrence, B.T., 2022. Association between land surface temperature and green volume in Bochum, Germany. Article 21. Sustainability 14 (21). https://doi.org/10.3390/su142114642.

Shi, D., Song, J., Huang, J., Zhuang, C., Guo, R., Gao, Y., 2020. Synergistic cooling effects (SCEs) of urban green-blue spaces on local thermal environment: a case study in Chongqing, China. Sustain. Cities Soc. 55, 102065. https://doi.org/10.1016/j.scs.2020.102065.

Singh, K.K., 2018. Urban green space availability in Bathinda City, India. Environ. Monit. Assess. 190 (11), 671. https://doi.org/10.1007/s10661-018-7053-0.

Smith, E.S., Fleet, C., Gosal, A.S., King, S., Walker, H., Willey, I., Scott, C.E., 2026. Which trees matter most? The role of private garden trees and woodland cover for 3–30-300 success in seven English cities. Urban For. Urban Green. 116, 129221. https://doi.org/10.1016/j.ufug.2025.129221.

Smith, R.M., Gaston, K.J., Warren, P.H., Thompson, K., 2005. Urban domestic gardens (V): relationships between landcover composition, housing and landscape. Landsc. Ecol. 20 (2), 235–253. https://doi.org/10.1007/s10980-004-3160-0.

Sousa-Silva, R., Duflos, M., Ordóñez Barona, C., Paquette, A., 2023. Keys to better planning and integrating urban tree planting initiatives. Landsc. Urban Plan. 231, 104649. https://doi.org/10.1016/j.landurbplan.2022.104649.

Sousa-Silva, R., Lambry, T., Cameron, E., Belluau, M., Paquette, A., 2023. Urban forests – Different ownership translates to greater diversity of trees. Urban For. Urban Green. 88, 128084. https://doi.org/10.1016/j.ufug.2023.128084.

Spano, G., Nobile, F., Giannico, V., Elia, M., Michelozzi, P., Bosco, A., Dadvand, P., Sanesi, G., Stafoggia, M., 2023. Two- and three-dimensional indicators of green and grey space exposure and psychiatric conditions and medicine use: A longitudinal study in a large population-based Italian cohort. Environ. Int. 182, 108320. https://doi.org/10.1016/j.envint.2023.108320.

Su, L., Kan, Z., Kwan, M.-P., 2025. Exploring the factors behind the discrepancy between two-dimensional and three-dimensional indicators of greenspace exposure. Ecol. Indic. 175, 113584. https://doi.org/10.1016/j.ecolind.2025.113584.

Svendsen, E.S., Campbell, L.K., McMillen, H.L., 2016. Stories, Shrines, and symbols: recognizing psycho-social-spiritual benefits of urban parks and natural areas. J. Ethnobiol. 36 (4), 881–907. https://doi.org/10.2993/0278-0771-36.4.881.

Taubenböck, H., Esch, T., Wurm, M., Roth, A., Dech, S., 2010. Object-based feature extraction using high spatial resolution satellite data of urban areas. J. Spat. Sci. 55 (1), 117–132. https://doi.org/10.1080/14498596.2010.487854.

Taubenböck, H., Reiter, M., Dosch, F., Leichtle, T., Weigand, M., Wurm, M., 2021. Which city is the greenest? A multi-dimensional deconstruction of city rankings. Comput. Environ. Urban Syst. 89, 101687. https://doi.org/10.1016/j.compenvurbsys.2021.101687.

Threlfall, C.G., Mata, L., Mackie, J.A., Hahs, A.K., Stork, N.E., Williams, N.S.G., Livesley, S.J., 2017. Increasing biodiversity in urban green spaces through simple vegetation interventions. J. Appl. Ecol. 54 (6), 1874–1883. https://doi.org/10.1111/1365-2664.12876.

Threlfall, C.G., Ossola, A., Hahs, A.K., Williams, N.S.G., Wilson, L., Livesley, S.J., 2016. Variation in Vegetation Structure and Composition across Urban Green Space Types. Front. Ecol. Evol. 4. https://doi.org/10.3389/fevo.2016.00066.

United Nations. (2020). The Sustainable Development Goals Report 2020. ⟨https://unstats.un.org/sdgs/report/2020/⟩.

Van Renterghem, T., 2019. Towards explaining the positive effect of vegetation on the perception of environmental noise. In: Urban Forestry & Urban Greening, Urban Green Infrastructure – Connecting People and Nature for Sustainable Cities, 40, pp. 133–144. https://doi.org/10.1016/j.ufug.2018.03.007.

Wang, R., Cao, M., Yao, Y., Wu, W., 2022. The inequalities of different dimensions of visible street urban green space provision: a machine learning approach. Land Use Policy 123, 106410. https://doi.org/10.1016/j.landusepol.2022.106410.

Wang, H.-F., Qureshi, S., Qureshi, B.A., Qiu, J.-X., Friedman, C.R., Breuste, J., Wang, X.-K., 2016. A multivariate analysis integrating ecological, socioeconomic and physical characteristics to investigate urban forest cover and plant diversity in Beijing, China. Ecol. Indic. 60, 921–929. https://doi.org/10.1016/j.ecolind.2015.08.015.

Weigand, M., Wurm, M., Droin, A., Stark, T., Staab, J., Rauh, J., Taubenböck, H., 2023. Are public green spaces distributed fairly? A nationwide analysis based on remote sensing, OpenStreetMap and census data. Geocarto Int. 38 (1), 2286305. https://doi.org/10.1080/10106049.2023.2286305.

Wildman, J., Shen, J., 2014. Impact of Income Inequality on Health. In: Culyer, A.J. (Ed.), Encyclopedia of Health Economics. Elsevier, pp. 10–14. https://doi.org/10.1016/B978-0-12-375678-7.00209-1.

Wolch, J.R., Byrne, J., Newell, J.P., 2014. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough. Landsc. Urban Plan. 125, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017.

World Health Organization Regional Office for Europe. (2016). Urban green spaces and health (WHO/EURO:2016-3352-43111-60341). Article WHO/EURO:2016-3352-43111-60341. ⟨https://iris.who.int/handle/10665/345751⟩.

Wurm, M., Taubenböck, H., Schardt, M., Esch, T., Dech, S., 2011. Object-based image information fusion using multisensor earth observation data over urban areas. Int. J. Image Data Fusion 2 (2), 121–147. https://doi.org/10.1080/19479832.2010.543934.

Wüstemann, H., Kalisch, D., Kolbe, J., 2017. Access to urban green space and environmental inequalities in Germany. Landsc. Urban Plan. 164, 124–131. https://doi.org/10.1016/j.landurbplan.2017.04.002.

Xia, T., Zhao, B., Xian, Z., Zhang, J., 2023. How to systematically evaluate the greenspace exposure of residential communities? A 3-D novel perspective using UAV photogrammetry. Article 6. Remote Sens. 15 (6). https://doi.org/10.3390/rs15061543.

Xu, C., Haase, D., Pauleit, S., 2018. The impact of different urban dynamics on green space availability: a multiple scenario modeling approach for the region of Munich, Germany. Ecol. Indic. 93, 1–12. https://doi.org/10.1016/j.ecolind.2018.04.058.

Zeng, H., Wang, J., Guan, M., Lu, Y., Liu, H., Zhao, D., 2023. Effects of vegetation structure and environmental characteristics on pollinator diversity in urban green spaces. Urban For. Urban Green. 84, 127928. https://doi.org/10.1016/j.ufug.2023.127928.

Zhang, J., Zhou, S., Xia, T., Yin, Y., Wang, X., Cheng, Y., Mao, Y., Zhao, B., 2024. Residential greenspace exposure, particularly green window-views, is associated with improved sleep quality among older adults: evidence from a high-density city. Build. Environ. 253, 111315. https://doi.org/10.1016/j.buildenv.2024.111315.

Zhao, N., Prieur, J.-F., Liu, Y., Kneeshaw, D., Lapointe, E.M., Paquette, A., Zinszer, K., Dupras, J., Villeneuve, P.J., Rainham, D.G., Lavigne, E., Chen, H., van den Bosch, M., Oiamo, T., Smargiassi, A., 2021. Tree characteristics and environmental noise in complex urban settings – A case study from Montreal, Canada. Environ. Res. 202, 111887. https://doi.org/10.1016/j.envres.2021.111887.

Zhou, L., Li, X., Zhang, B., Xuan, J., Gong, Y., Tan, C., Huang, H., Du, H., 2022. Estimating 3D green volume and aboveground biomass of urban forest trees by UAV-Lidar. Article 20. Remote Sens. 14 (20). https://doi.org/10.3390/rs14205211.