



## Original article

## Beyond public inventories: Remote sensing–based assessment of urban tree ecosystem services

Andrea Sofía García de León<sup>a,\*</sup>, Thomas Rötzer<sup>b</sup>, Tobias Leichtle<sup>c</sup>, Stephan Pauleit<sup>b</sup>,  
John Friesen<sup>a</sup>, Klaus Martin<sup>d</sup>, Tobias Ullmann<sup>e</sup>, Hannes Taubenböck<sup>a,c</sup>

<sup>a</sup> Earth Observation Research Cluster, Department of Global Urbanization and Remote Sensing, Institute of Geography and Geology, University of Würzburg, Germany

<sup>b</sup> Chair for Strategic Landscape Planning and Management, School of Life Sciences Weihenstephan, Technical University of Munich (TUM), Freising, Germany

<sup>c</sup> Department of Georisks and Civil Security, German Remote Sensing Data Center, German Aerospace Center (DLR), Weßling, Germany

<sup>d</sup> Company for Remote Sensing and Environmental Research (SLU), Germany

<sup>e</sup> Earth Observation Research Cluster, Department of Remote Sensing, Institute of Geography and Geology, University of Würzburg, Germany

## ARTICLE INFO

## Keywords:

Ecosystem services estimation

Urban trees

Remote sensing

CityTree model

Urban planning

## ABSTRACT

Urban trees provide important ecosystem services (ESS), but their contributions are often undervalued and less acknowledged due to the complexity of quantifying them. Therefore, ESS assessment for urban trees at the individual tree level using ESS models is crucial for a more knowledge-based management of urban green spaces. In this study, we used very high-resolution aerial and satellite-based remote sensing imagery to derive the geospatial input for the CityTree model to estimate regulating ESS from over 160,000 individual trees in Munich, Germany. Our assessment includes both, trees on public and private land and enables fine-scale spatial modeling of eight ESS (carbon storage, carbon sequestration, CO<sub>2</sub> sequestration, evapotranspiration of trees, runoff under the tree, transpiration, cooling by transpiration and shading). We found that public trees, especially those in recreational areas such as parks and woodlands, contribute largely to ESS provision. Private trees also play a meaningful role by contributing around one third of the total ESS. A statistical comparison with the tree inventory data revealed good agreement between the two datasets. However, we also found systematic measurement differences, possibly due to rounding in field measurements and limitations in remote sensing datasets. However, the size effect of these differences is small in practical terms, indicating that both data sources are comparable and complementary. Our findings support the use of remote sensing as a scalable, area-wide, consistent, and resource-efficient approach for urban ESS estimations.

## 1. Introduction

Urban green infrastructure, especially trees, delivers critical ecosystem services (ESS) that enhance well-being and mitigate urban challenges such as air pollution, heat islands, energy use, flash floods, and stress (Hanna et al., 2024; Hao et al., 2023; Livesley et al., 2016). The Millennium Ecosystem Assessment (MEA, 2005) classifies ESS into regulating, provisioning, supporting and cultural services. Among these, regulating ESS are particularly critical for urban resilience, as they help to mitigate environmental stressors and climate-related risks (Barbier, 2013). Urban trees contribute with many regulating ESS, including carbon sequestration (Chen, 2015), shading (Rahman et al., 2019), cooling through transpiration (Aram et al., 2019; Rahman et al., 2020), and runoff reduction (Berland et al., 2017; Carlyle-Moses et al., 2020).

Precise information on the magnitude and spatial distribution of urban trees regulating ESS is essential to increase their perceived value and contribute to more knowledge-based management of urban green spaces (Cimburowa and Berghauser Pont, 2021; Mengist et al., 2020). However, measuring these ESS in highly variable urban environments is challenging due to the complexity of the ecological processes and the requirement of large-scale data in adequate high resolution (Mengist et al., 2020; Villamagna et al., 2013). Urban tree ESS models are widely used to quantify some of the ESS offered by trees using information on the characteristics of the plants, climatic conditions, and in some cases soil conditions (Rötzer et al., 2020). Some of the most robust and frequently used models are the UFORE (Nowak and Crane, 2000) further developed as i-Tree Eco (Nowak et al., 2018), CITYgreen (Peng et al., 2008), and CityTree (Rötzer et al., 2019). Among these models, CityTree

\* Correspondence to: Department of Global Urbanization and Remote Sensing, University of Würzburg, John-Skilton-Str. 4a, Würzburg 97074, Germany.  
E-mail address: [andrea-sofia.garcia-de-leon@uni-wuerzburg.de](mailto:andrea-sofia.garcia-de-leon@uni-wuerzburg.de) (A.S. García de León).

<https://doi.org/10.1016/j.ufug.2026.129382>

Received 8 August 2025; Received in revised form 14 January 2026; Accepted 27 February 2026

Available online 1 March 2026

1618-8667/© 2026 The Authors. Published by Elsevier GmbH. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

stands out as the only process-based model integrating physiological functions instead of empirical and statistical relationships. Additionally, it can simulate ESS at different time scales and is focused on some of the most common tree species in Central European cities (Rötzer et al., 2020).

A major challenge of the urban tree ESS models is their reliance on detailed data at the individual tree level, which is often obtained from official tree inventory records or field campaigns (e.g., Alvarado, 2025; Song et al., 2020). Even though these data are locally detailed and comprehensive, they are resource-intensive to collect and maintain. Moreover, such data are often only available for public land (Baines et al., 2020; Nowak et al., 2008), which leaves out the important contribution of private trees. Therefore, identifying more cost-effective, area-wide methods for collecting tree data is critical for more accurate large-scale ESS estimations.

In this context, remote sensing is a powerful method for characterizing urban green spaces and their trees. It has demonstrated the ability to detect urban vegetation at various scales (e.g., Shahtahmassebi et al., 2021), from broad canopy cover mapping (Guo et al., 2023; Taubenböck et al., 2021) to the identification of individual trees (e.g., Wallace et al., 2021). Additionally, remote sensing techniques can provide valuable information on tree dimensions (Lee et al., 2016; Leichtle et al., 2021; Pauleit et al., 2022) and, in some cases, distinguish between tree genera and species (e.g., Fang et al., 2020; García de León et al., 2025).

Reviews by García-Pardo et al. (2022) and Sharma et al. (2025) highlight the potential of remote sensing methods in urban tree ESS estimation. According to García-Pardo et al. (2022), remote sensing has the potential to provide vegetation data for estimating ESS after the appropriate method is identified based on data availability, geographical scale, and image resolution. Similarly, Sharma et al. (2025) found that, although many studies have estimated parameters required for ESS models such as i-Tree Eco, these data have not yet been commonly integrated into the models. One of the data integration examples is presented by Sharma et al. (2024), who used Landsat satellite images and a Digital Surface Model (DSM) to estimate tree parameters and feed the i-Tree Eco model to simulate pollution uptake. They compared their results with tree inventory data from a park in California, USA, finding comparable values. Cimburova and Barton (2020) fed the i-Tree Eco model with data derived from an aerial laser scanning (ALS) to complement the tree attributes of a municipal inventory with 30,000 trees in Oslo, Norway. Likewise, Zięba-Kulawik et al. (2021) proposed a methodology to combine ALS point clouds with field measurements to assess tree parameters required by the i-Tree Eco model to estimate ESS for 264,471 trees in Racibórz, Poland.

The previous studies have explored the use of different types of remote sensing data to estimate ESS of urban trees. However, these approaches rely on the i-Tree Eco model and most of them use ALS data. To the best of our knowledge, no study has yet combined high-resolution optical remote sensing data with a process-based model for ESS estimations at the individual tree level. This combination would allow for a more cost-efficient approach, providing high transferability and repeatability. Remote sensing techniques are capable to provide large-scale inputs for the process-based CityTree model (e.g., tree height, crown dimensions and species), which would decrease the cost and time of the data collection, facilitate the coverage of trees on private grounds, add a spatial dimension to the simulation, and improve the scalability of the model. Therefore, the overarching goal of this research is to test the potential of remote sensing data for scaling up estimations of ESS of urban trees, particularly in comparison with cadaster-derived measurements. We have three main objectives: (i) We analyze the spatial distribution of selected ESS (carbon storage, carbon sequestration, CO<sub>2</sub> sequestration, evapotranspiration of trees, runoff, transpiration, cooling by transpiration and by shading) for an area of 44 km<sup>2</sup> in the center of Munich, Germany using a comprehensive remote sensing-based dataset and the CityTree model. (ii) We use the comprehensive coverage of remote-sensing data to evaluate the differences between ESS provided

by trees under different land ownership types: street trees, trees in recreation areas and private trees. This differentiation is based on the assumption that varying conditions, species, and management practices likely result in distinct ESS contributions. (iii) We compare ESS estimates derived from remote sensing with those based on the urban tree cadaster to identify similarities and differences between the two data sources and to assess the extent to which remote sensing can reproduce patterns while addressing spatial and thematic limitations of the cadastral data. This comparison is critical to validate our results and to evaluate remote sensing as a complementary data source for large-scale urban tree ESS assessment.

## 2. Materials and methods

### 2.1. Overview of the study area

This study was conducted in the central area of the city of Munich, Germany, covering approximately 44 km<sup>2</sup>. It includes the old town, two train stations, public parks such as part of the *Englischer Garten* and *alter Nordfriedhof*, other recreational areas, and many commercial and residential zones. We selected this area because the tree inventory and remote sensing-derived tree data are available. Additionally, the City-Tree model has been adapted for the species present in the region (Rötzer et al., 2019). Fig. 1 shows the study area in the context of the administrative area of Munich, the detailed landownership classification derived from ATKIS (2023), and the names of locations of interest.

Munich presents a temperate climate characterized by warm summers (Beck et al., 2018), an average annual temperature of 10.1 °C, and around 940 millimeters of annual precipitation from 1991 to 2020 (DWD Climate Data Center, 2025). Land cover data from 2019 generated by the German Aerospace Center indicate that vegetation accounts for 62.18% of Munich's administrative area. These include different types of vegetation distributed in public green spaces, vegetation patches on private land, as well as suburban natural areas managed as urban parks and forests.

### 2.2. Data

#### 2.2.1. Tree data

The tree data used in this study comes from two sources: the official tree cadaster and remote sensing-derived datasets. The cadaster was obtained from Munich's official tree inventory and includes information on tree location, genus, species, vitality, height, crown size, and diameter at breast height (dbh) for about 78,300 public trees in the city center. These data were collected for the Landeshauptstadt München in 2021.

Remote sensing-based tree crown segments were produced by Leichtle et al. (2021) from very high-resolution (VHR) aerial images using a Local Maximum filter and watershed segmentation. These segments were generated from 10 cm resolution RGBI aerial images acquired in 2017 and 2019 by the Agency for Digitization, High-Speed Internet and Surveying. The imagery was provided by Geobasisdaten © Landeshauptstadt München – Kommunalreferat – GeodatenService 2021.

Tree genus classification was obtained from García de León et al. (2025), using a hierarchical classification approach. This method used bi-temporal WorldView-2 satellite imagery, acquired in 2019 and 2021 provided by European Space Imaging. These images offer a spatial resolution up to 46 cm, respectively and include eight multi-spectral bands: coastal blue, blue, green, yellow, red, red edge, and two near-infrared bands. The resulting dataset includes more than 160,000 trees for five tree genera: *Acer*, *Tilia*, *Robinia*, *Aesculus*, and *Populus*.

#### 2.2.2. Ancillary data

We used a normalized digital surface model (nDSM) to observe the height of above-ground objects such as buildings or trees. It was derived

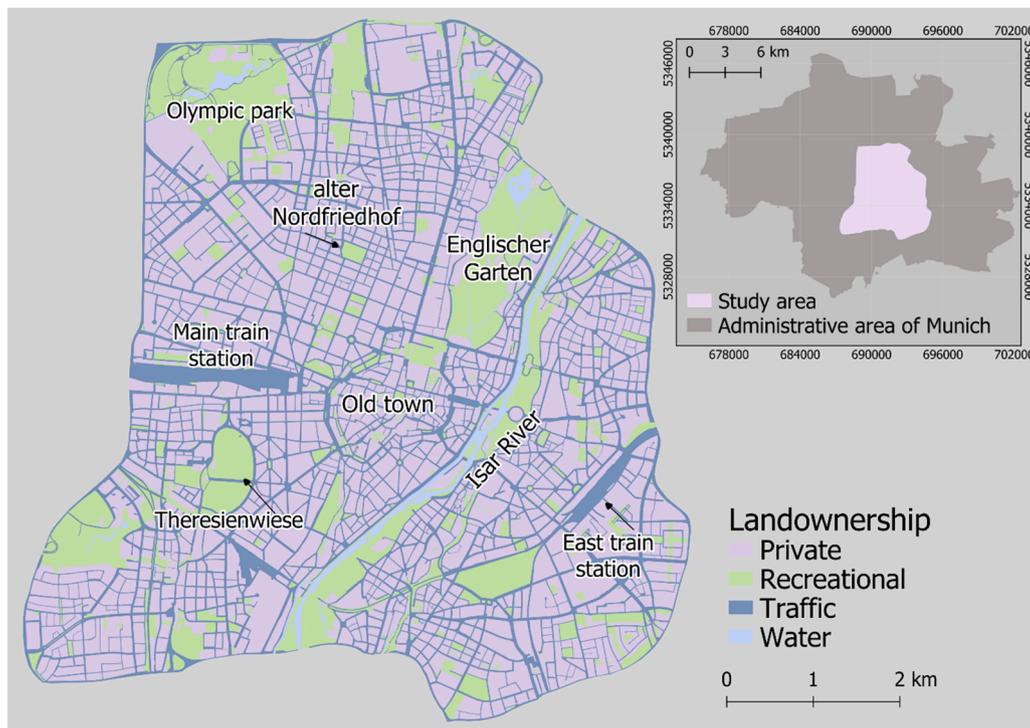


Fig. 1. Study area showing the spatial distribution of landownership classes (private, recreational, and traffic) reclassified from ATKIS (2023), along with the names of key landmarks and locations of interest within the city.

from high-resolution aerial images using stereophotogrammetry, as described by d'Angelo and Kurz (2019). The aerial images were provided by Geobasisdaten © Landeshauptstadt München – Kommunalreferat – GeodatenService 2021. Additionally, we used the Actual Use layer (ATKIS, 2023) available from the open data portal of the federal state of Bavaria (<https://geodaten.bayern.de/opengeodata/>). This dataset categorizes the study area into 14 land use classes, including residential areas, road traffic, and recreational, leisure, and sports facilities. The classification is based on aerial images, agricultural and forestry administration data, as well as cadastral surveys. In our analysis, land use was used as a proxy to infer land ownership, allowing us to distinguish between public and private tree locations in the absence of explicit ownership information.

### 2.3. Methods

#### 2.3.1. The CityTree model for ESS assessment

CityTree is an urban tree growth and ESS model for individual trees developed by Rötzer et al. (2019). One of the most important characteristics of this model is that its simulations are based on biological, physical, and chemical processes, which defines it as a process-based model. This model focuses on the following regulating ESS: carbon storage, carbon sequestration CO<sub>2</sub> sequestration, evapotranspiration of trees, runoff reduction, transpiration, and cooling by transpiration and shading. The model has eight interconnected modules: climate, plant development, water balance, photosynthesis, respiration, allocation, shading, and cooling. Each module simulates specific tree processes and characteristics which in turn are linked to key ESS.

The climate module requires meteorological data, including temperature, radiation, and precipitation. The plant development module simulates seasonal dynamics in leaf area and crown characteristics, which influence transpiration, shading, and photosynthesis. The water balance module estimates transpiration, runoff, and soil moisture conditions. The cooling module quantifies energy release through evapotranspiration. Photosynthesis and respiration modules estimate carbon assimilation, while allocation module distributes assimilated carbon

into tree compartments: roots, stem, branches and leaves, determining growth and structural traits like height and crown size. This feeds back into the Leaf Area Index and therefore affects shading, transpiration, and carbon storage. The shading module calculates shaded area and shade density based on tree height and crown dimensions, contributing to microclimate regulation. Detailed descriptions and equations of these relationships can be found in Rötzer et al. (2019).

Originally, the model uses field-based tree data and monthly climate data, such as the long-term mean values (1991–2020) (Centre for Urban Ecology and Climate Adaptation-TUM, 2024a; DWD Climate Data Center, 2025). Soil properties can be inserted individually for each tree or selected from a classification of soil types (Centre for Urban Ecology and Climate Adaptation-TUM, 2024b). For our study, most climate and soil parameters were considered constant, as no spatially resolved data were available (see Table 1). On the other hand, tree characteristics and soil sealing were estimated by remote sensing, statistical methods or field surveys at the individual tree level (see Table 1).

#### 2.3.2. Derivation of model input parameters from remote sensing

In this study, we used high-resolution geospatial data derived from aerial imagery (orthophotos and nDSM) and bi-temporal Worldview satellite imagery to extract tree-level parameters required as input for the CityTree model.

**2.3.2.1. Tree dimensions.** Tree dimensions are fundamental for estimating ESS, such as carbon storage, transpiration, and shading potential, as they reflect the structural capacity and age of each tree (Rötzer et al., 2019). Crown diameter was estimated from tree segments derived from Leichte et al. (2021), who achieved 88.1% overall accuracy using a marker-controlled watershed segmentation. We determined crown diameter by extracting each segment's centroid, measuring distances to the polygon edges, averaging them, and doubling the result. Tree height was estimated by extracting nDSM values within each tree segment. To minimize the influence of potential outliers, we defined the height as the 90th percentile of the height distribution for each segment. Dbh was estimated using species-specific allometric equations, following the

**Table 1**  
Input parameters for the CityTree model.

| Category                | Parameter                           | Value                 | Source              |                                       |                  |
|-------------------------|-------------------------------------|-----------------------|---------------------|---------------------------------------|------------------|
|                         |                                     |                       | Literature/ records | Remote Sensing or statistical methods | Field collection |
| Tree characteristics    | Species (genus)                     | Variable              |                     | X                                     | X                |
|                         | Dbh (cm)                            | Variable              |                     | X                                     | X                |
|                         | Height (m)                          | Variable              |                     | X                                     | X                |
|                         | Crown diameter (m)                  | Variable              |                     | X                                     | X                |
|                         | Skyview Factor                      | Variable              |                     | X                                     |                  |
| Climate characteristics | Radiation (J/cm <sup>2</sup> )      | 311 – 1855            | X                   |                                       |                  |
|                         | Temperature (°C)                    | 0.9 – 19.6            | X                   |                                       |                  |
|                         | Humidity (%)                        | 65 – 83               | X                   |                                       |                  |
|                         | Wind speed (m/s)                    | 2.2 – 2.9             | X                   |                                       |                  |
|                         | Precipitation (mm)                  | 45.5 – 120.9          | X                   |                                       |                  |
|                         | CO <sub>2</sub> concentration (ppm) | Constant (400)        | X                   |                                       |                  |
| Soil characteristics    | Soil type                           | Constant (Sandy loam) | X                   |                                       |                  |
|                         | Soil sealing (%)                    | Variable              |                     | X                                     |                  |
|                         | Field capacity (vol%)               | Constant (25)         | X                   |                                       |                  |
|                         | Wilting point (vol%)                | Constant (8)          | X                   |                                       |                  |
|                         | Rooting depth (cm)                  | Constant (80)         | X                   |                                       |                  |

inverse equations method of Pretzsch et al. (2015) or Mengxuan (2025).

**2.3.2.2. Tree genera.** Tree species or genera strongly influence physiological functions and ESS potential (Rahman et al., 2019; Rötzer et al., 2019). We used the tree genera classification developed by García de León et al. (2025). They developed an approach using a random forest machine learning algorithm achieving up to 87.7% of accuracy. This method used bi-temporal WorldView images and tree cadaster data to perform hierarchical classification according to the land use, allowing the area-wide identification of five different tree genera in the study area.

**2.3.2.3. Sky view factor (SVF).** Openness is a key factor for estimating direct solar radiation and light availability, which directly influences photosynthetic efficiency and affects the magnitude of some ESS, such as shading. This parameter was assessed using the SVF, which quantifies the proportion of sky visible from a given point. The SVF was calculated at each tree centroid using the nDSM. We used the SAGA toolbox within the QGIS software for this calculation, quantifying the openness of the surrounding urban landscape for each tree (Böhner and Antonić, 2009).

**2.3.2.4. Soil sealing.** Soil sealing directly impacts water infiltration and root development and is a key factor in assessing ESS related to water-balance (Morgenroth and Buchan, 2009; Rahman et al., 2013; Rötzer et al., 2019). Field data were used to calculate sealing levels following Moser-Reischl et al. (2021) and estimated the mean for each of the 14 land use classes from ATKIS (2023). Each tree's sealing value was assigned based on the land use class corresponding to its centroid location.

### 2.3.3. Spatial analysis of ESS distribution

Given the importance of the ESS distribution for urban tree management, we conducted a spatial analysis, in which we examined ESS spatial patterns. First, we generated kernel density heat maps for all eight ESS to examine spatial intensity and distribution across the study area. These maps were weighted by the respective ESS values. Runoff reduction was calculated by dividing modeled runoff under each tree by annual precipitation, subtracting the result from 1, and multiplying by 100 to obtain percentage reduction.

Then, we estimated ESS efficiency by normalizing each ESS indicator by the tree crown area. This approach allowed us to identify areas where trees provide relatively high or low ESS per unit crown area, highlighting locations where structural characteristics, species composition, or site conditions influence ESS performance independently of the tree size or density. These maps were used to detect areas of interest, such as locations with relatively high tree cover but low ESS provision.

Finally, to reduce the redundancy among highly spatially correlated ESS, we conducted a Principal Component Analysis (PCA) on the full set of ESS estimates. PCA was used to identify dominant gradients in ESS provision that could be clustered for the selection of representative ESS for spatial mapping.

### 2.3.4. Comparison of ESS provision across landownership types

We compared tree metrics and ESS between public and private land using the entire remote sensing dataset. This is important to assess the influence of management practices and to quantify the portion of ESS that may be overlooked when private trees are excluded. We used the land use classes suggested by García de León et al. (2025) as a proxy for land ownership, assuming they reflect different planting, maintenance, and planning practices. We used the Actual Land Use dataset (ATKIS, 2023), as it is based on local administrative data, which leads to higher accuracy compared to broader national or global datasets. Land use types related to streets and railways were grouped into a 'traffic areas' category, which is predominantly characterized by street trees managed by public authorities. For clarity and consistency, trees within this category are hereafter referred to as street trees, acknowledging that the class also includes a smaller proportion of trees located along rail infrastructure. Recreational areas, including squares, water bodies, woodlands, sports facilities, leisure zones, and cemeteries, were grouped due to their shared patterns of public management and tree characteristics. Both categories, traffic and recreational, were defined as public tree areas. The remaining land use types, such as mixed-use zones, industrial areas, and residential neighborhoods, were classified as private. The distribution of these classes is shown in Fig. 1. We then analyzed how tree metrics and ESS values varied across public and private areas to reveal spatial and structural differences.

### 2.3.5. Comparison between cadastral- and remote sensing-based data

We compared remote sensing results with cadaster data to analyze the advantages and disadvantages of both. We generated scatterplots to visualize relationships between tree metrics derived from each source. Additionally, we estimated ESS values using the CityTree model with both datasets to compare outputs. For these comparisons, we applied a strict matching criterion, counting only cases where tree points from the cadaster and tree crowns from remote sensing presented a one-to-one relationship. We found 27,673 trees that presented this condition and therefore were used for the analysis. To visualize the distribution of results, we used violin plots. Additionally, we performed a statistical comparison across all modeled ESS variables to assess the agreement between ESS estimates derived from remote sensing and from the tree cadaster. We applied two statistical measures:

- a. Cohen's d (Cohen, 1988) was used to quantify standardized mean differences between the two datasets, helping identify the magnitude of any systematic bias.
- b. Welch's t-test (Welch, 1947) was applied to test for statistically significant differences in mean values between the remote sensing and cadaster-based datasets.

### 3. Results

#### 3.1. Spatial distribution of ESS in the study area

Fig. 2 shows the spatial analyses of the ESS modeled by CityTree in central Munich. The PCA demonstrated that most ESS share a common spatial gradient driven by tree structure, resulting in similar spatial patterns. To reduce redundancy and improve interpretability, we retained representative maps for structurally driven ESS, like CO<sub>2</sub> sequestration (Figs. 2a and 2b) and cooling by shading (Figs. 2c and 2d), and functionally distinct services like transpiration (Figs. 2e and 2f) and runoff reduction by trees (Figs. 2g and 2h).

We used kernel-density maps, with the ESS as weights, to visualize spatial patterns in the intensity of the ESS. In the density plots, we can observe higher concentrations of ESS in areas with larger and denser tree canopies. For instance, the *Englischer Garten* (northeast) stands out as the main hotspot, followed by the green corridor along the Isar River. In contrast, central areas near the main train station and the old town, in the center of the map, show low ESS densities, reflecting densely built areas and low vegetation share. Runoff reduction (Fig. 2e) presents a

slightly different spatial pattern, as it is strongly influenced by soil permeability. In the central areas of parks, runoff reduction by trees is lower because these zones are already highly permeable and naturally facilitate infiltration of surface runoff.

Normalizing the ESS estimates by crown area reveals spatial patterns that are different to those observed for density-based values. Fig. 2b shows that high CO<sub>2</sub> sequestration values are observed in large green spaces, e.g., the *Englischer Garten* and areas along the Isar river. In contrast, long, densely built street areas show lower sequestration efficiency. Cooling by shading per unit crown area (m<sup>2</sup>) shows a much more heterogenous spatial pattern (Fig. 2d). High and low values are mixed across the study area, with no clear clustering. Nevertheless, some streets consistently display lower shading efficiency.

For runoff reduction efficiency (Fig. 2f), a consistent pattern is noticeable, with large parks exhibiting comparatively low values. In contrast, some streets present higher values. This reflects the role of soil permeability, as highly permeable park soils already promote infiltration and therefore limit the additional runoff reduction from trees. Transpiration per unit crown area (Fig. 2h) shows a relatively similar spatial pattern, lower values are frequently observed along streets and in densely built areas, while lower values dominate large parks and other green spaces. However, transpiration efficiency does not form uniform patches but instead shows substantial small-scale variability.

The zoomed in maps provide additional insights into fine-scale variability of ESS that is not visible at the city scale. In general, we see that most of the ESS density is concentrated where the trees are concentrated. However, the maps of ESS normalized to the crown area

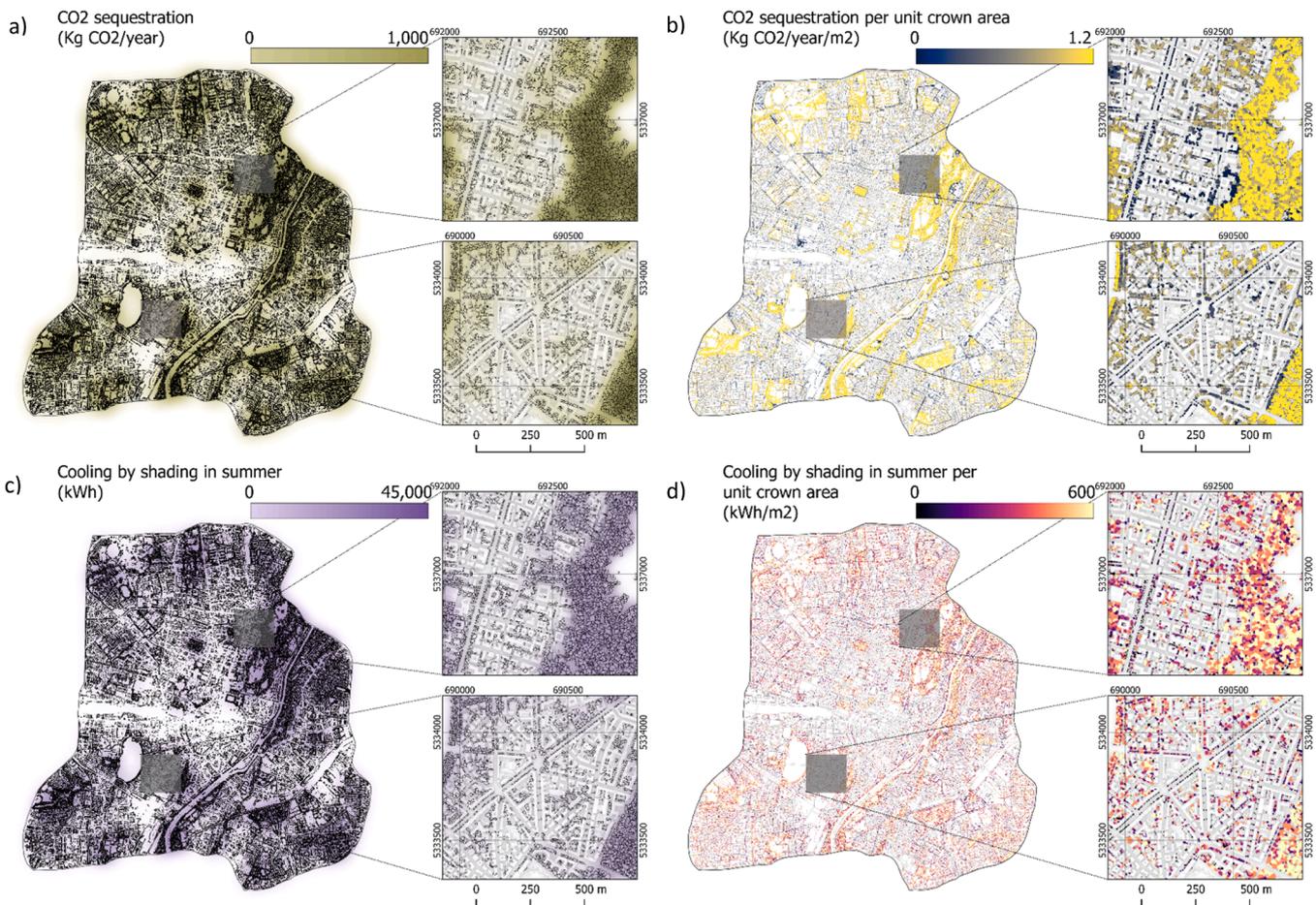


Fig. 2. Spatial distribution of urban trees' ecosystem services in the central area of Munich. (a) density of CO<sub>2</sub> storage in kg/year, (b) CO<sub>2</sub> storage normalized by crown area in kg/year/m<sup>2</sup>, (c) transpiration in mm/year, (d) transpiration normalized by crown area in mm/year/m<sup>2</sup>, (e) percentage of runoff reduction by trees, (f) percentage of runoff reduction normalized by crown area, (g) cooling by shading in summer in kWh, and (h) cooling by shading in summer normalized by crown area in kWh/m<sup>2</sup>.

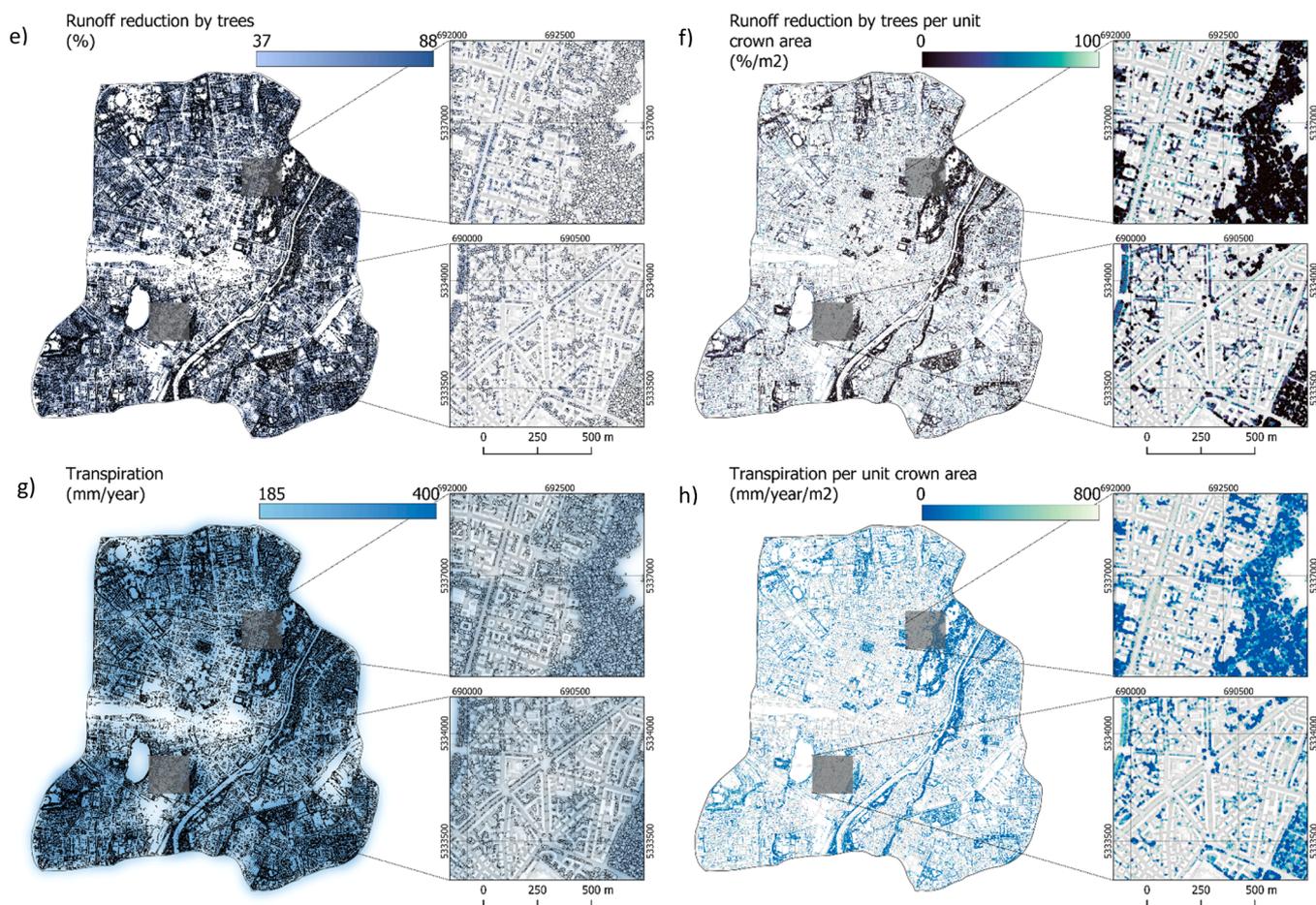


Fig. 2. (continued).

show that trees with similar crown areas can exhibit markedly different ESS efficiencies depending on other conditions like tree genera or soil permeability. In larger green spaces, individual trees often display higher and more homogenous CO<sub>2</sub> sequestration per unit crown area. Cooling by shading per unit crown area shows a much more heterogeneous pattern, which can be observed in the corner of the *Englischer Garten*. However, some streets show consistent lower values. Runoff reduction by trees and transpiration efficiency show an inverse pattern: higher values frequently occur along streets and in densely built areas, while lower values dominate park interiors. These localized patterns highlight the strong influence of micro-scale structural and contextual factors on ESS provision.

### 3.2. Comparison between different landownership classes

We classified the 161,005 trees characterized with remote sensing according to their landownership context. 87,007 trees were classified as private and 73,998 as public: 42,053 in recreational areas and 31,945 in traffic areas.

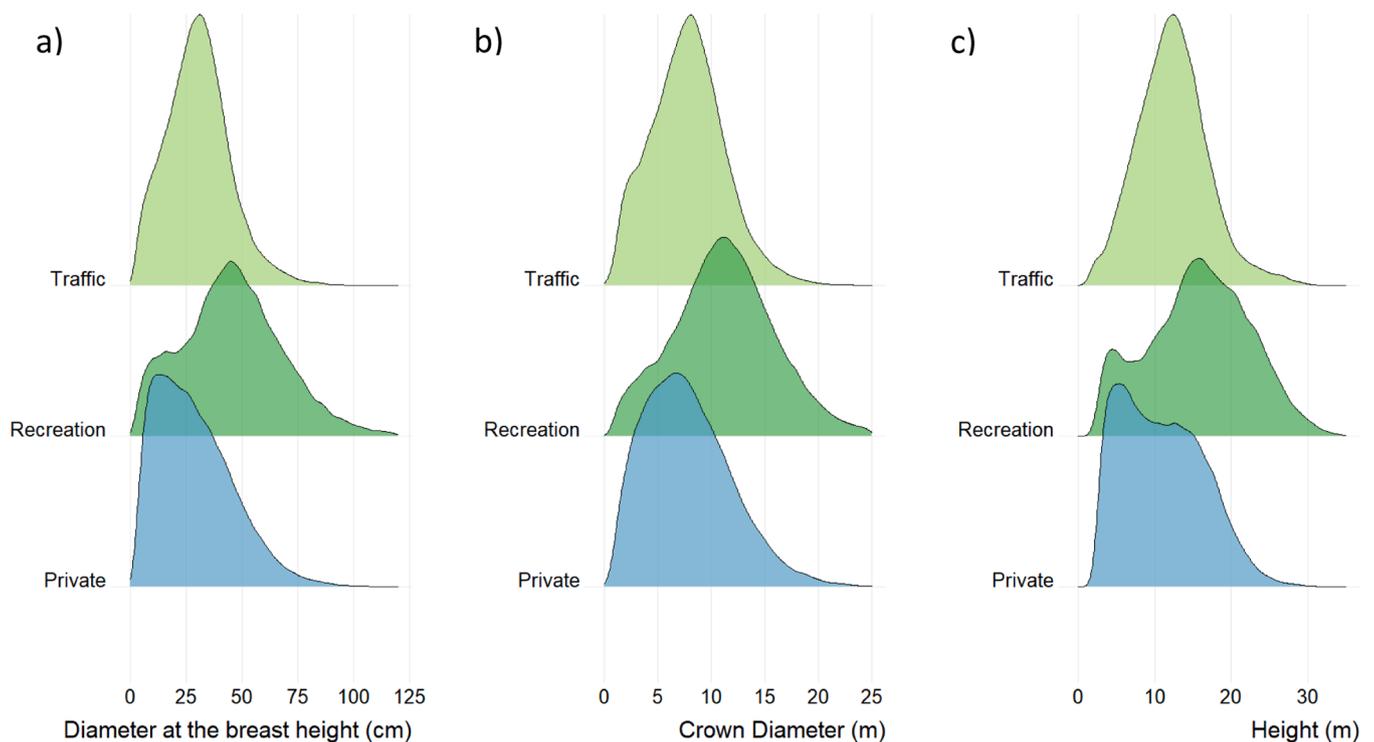
Fig. 3 presents the distribution of three key tree metrics for private trees and trees in two different public contexts. Trees in recreational areas showed a slightly right-skewed dbh distribution, suggesting the presence of larger, older trees. On the other hand, private trees presented smaller dbh values, most commonly by around 10 cm. We observed a similar pattern crown diameter (Fig. 3b). Private and street trees tend to have smaller crowns, likely reflecting younger trees, space constraints, poorer environmental conditions, or pruning. In recreational areas, crown diameters were more uniformly distributed, with a higher proportion exceeding 10 m. Tree height patterns followed the

same trend (Fig. 3c), though with sharper peaks. Private trees and recreational trees seem to have two peaks, one around 5 m and the other one around 15 m.

Fig. 4 shows the distribution of total ESS provided by trees across different landownership types. Despite being lower in numbers, public trees contributed more to ESS provision than private trees. Public trees contributed between 57.2% and 63.4% of the ESS analyzed. Among public trees, those located in recreational areas showed the highest ESS contributions. While private trees contributed less than public trees, their contribution remains considerable with values higher than 36% for all the ESS. With more than a third of ESS, it is clear that any city-wide analysis based only on public tree inventories considerably underestimates urban trees ESS.

We excluded runoff and transpiration from the comparative analysis due to methodological limitations related to the units that hinder meaningful aggregation. Both ESS are expressed in units of depth per unit area (mm/year), which are not directly additive across spatially heterogeneous elements such as individual trees. Without area-normalization or conversion to volumetric metrics (e.g., liters/year), direct comparison or stacking across trees or spatial units would have been misleading.

Additionally, although recreational areas contain only 24% more trees than traffic areas (10,108 more trees), their ESS contributions were substantially larger across all services. We also observed that the relative contribution from private and street trees vary depending on the specific ESS, suggesting that tree characteristics and local conditions influence ESS provision differently.



**Fig. 3.** Differences in tree structure across different land ownership classes. Private trees are represented in blue, while public trees, categorized into traffic and recreation areas, are shown in green. The height of each distribution curve corresponds to the frequency of trees at a given value. (a) Diameter at breast height in cm (b) crown diameter in m and c) tree height in m.

### 3.3. Comparison between remote sensing and cadastral data

We conducted comparative analyses using the 27,673 trees with matching records in the cadaster and remote sensing datasets. Due to the general nature of the cadaster data, these are trees predominantly on public land.

The first analysis compared tree metrics estimated from remote sensing products with the tree metrics contained in the cadastral records. Fig. 5 shows these relationships for tree height, dbh, and crown diameter. Overall, remote sensing results slightly overestimated metrics for smaller trees and underestimated those for larger trees. Additionally, tree height and crown diameter (Figs. 5a and 5b) present vertical clusters in the cadastral values that affected the metric relationships.

A summary of ESS estimates from the CityTree model using cadastral and remote sensing data is shown in Fig. 6. Overall, both approaches captured similar patterns, ranges and trends, especially for carbon storage, transpiration and runoff under the tree. However, remote sensing estimates had smoother distributions, while cadaster values appeared more multimodal. Medians from remote sensing were also consistently slightly lower across all ESS.

Statistical comparisons (Table 2) revealed different degrees of agreement depending on the ESS. Carbon storage, carbon sequestration, CO<sub>2</sub> sequestration, evapotranspiration of trees, cooling by transpiration and shading showed relatively small standardized mean differences (Cohen's *d* between 0.2 and 0.4). Transpiration and runoff had extremely small effect sizes (Cohen's *d* < 0.05), suggesting close agreement between both datasets. Despite these high correlations, Welch's *t*-tests revealed statistically significant differences for all ESS variables ( $p < 0.01$ ). This suggests a statistically significant difference, but small in practical terms.

## 4. Discussion

This study evaluated the potential of remote sensing to support large-scale urban tree ESS assessment, with a particular focus on how remote

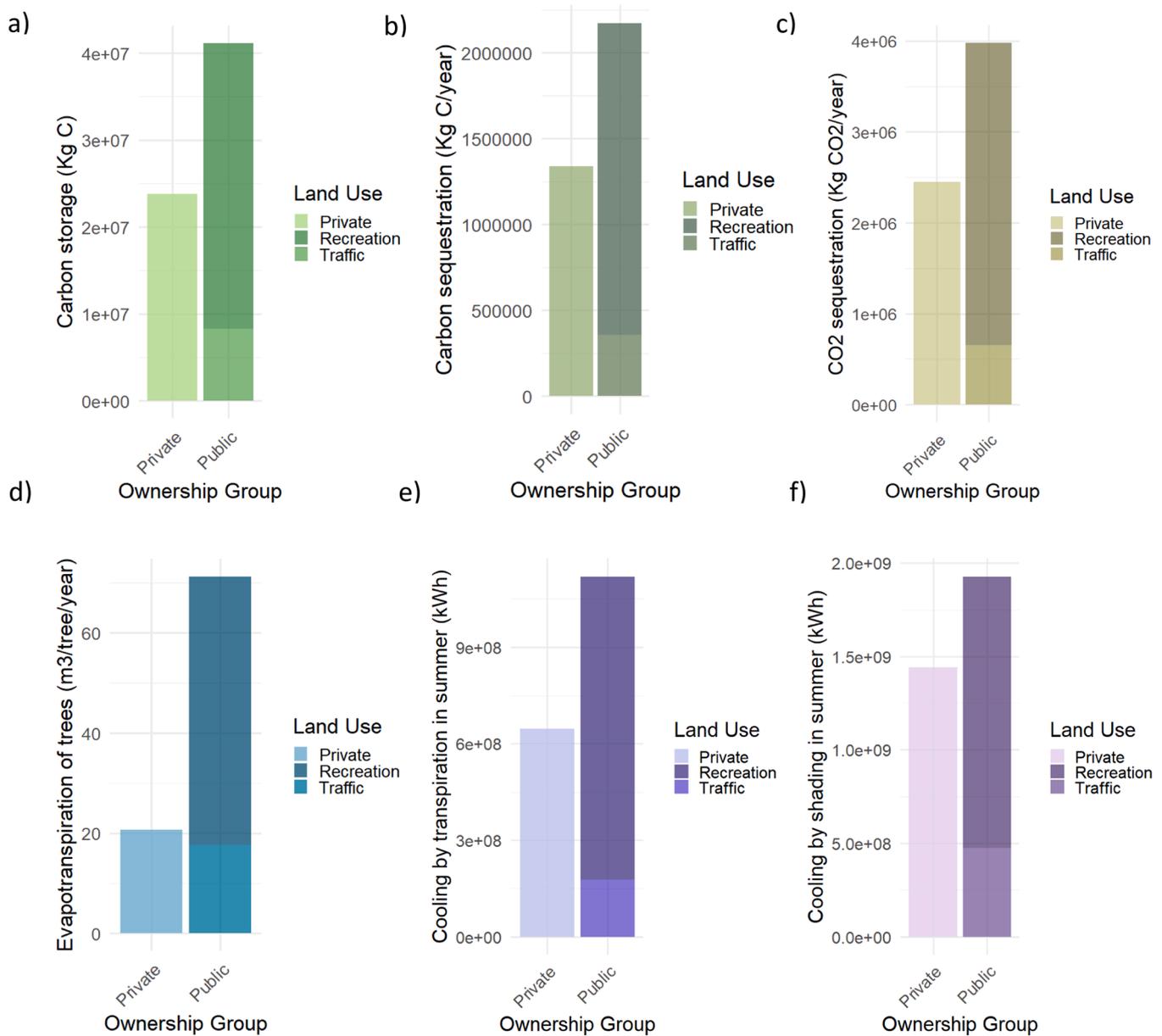
sensing-based estimates compare to those derived from official urban tree cadaster data. Our results show that remote sensing is a valuable and effective tool as it enabled the identification of spatial patterns and showed good agreement with ESS modelled from cadastral data. Our methods also detected trees in private areas, which are often missing in cadastral records, i.e. it allows for a more comprehensive, area-wide analysis and increases transferability, repeatability and significance. We found that private trees make an important contribution to ESS, highlighting their often-overlooked ecological role (Hutt-Taylor and Ziter, 2022). While slight underestimations occurred in some metrics, remote sensing provided broader spatial coverage than traditional inventories.

We propose a scalable, replicable method for spatially explicit ESS modeling at the individual tree level in urban environments. Using remote sensing techniques, we estimated tree parameters required by the CityTree model, including height, crown diameter, genus, and environmental context variables like SVF and soil sealing. These were estimated for over 161,000 trees in Munich, Germany with different degrees of accuracy. This approach is particularly valuable for large-scale applications, as it reduces the need for resource-intensive fieldwork while maintaining individual-level resolution.

The CityTree model enables the estimation of several regulating ESS at the individual tree level: carbon storage, carbon sequestration, CO<sub>2</sub> sequestration, transpiration, evapotranspiration of trees, runoff reduction by trees, and cooling by transpiration and by shading. While the model commonly relied on field-based tree inventories (Rötzer et al., 2024, 2019), our study provides an alternative by applying it to remote sensing-derived input data.

Compared to existing studies (e.g., Sharma et al., 2024; Zięba-Kula-wik et al. 2021; Cimburova and Barton, 2020), our approach introduces several methodological advances. We leverage VHR optical images and a model adapted to Central European tree species. We also incorporate an automatic remote sensing-based tree genus classification to our algorithm (García de León et al., 2025).

Beyond the methodological contribution, our geographical analysis



**Fig. 4.** Urban trees' ecosystem services values categorized by land ownership. Public trees are shown in darker shades, while private trees are represented in lighter shades. (a) Carbon storage in kg of carbon, (b) carbon sequestration in kg C per year, (c) CO<sub>2</sub> sequestration in kg/year, (d) evapotranspiration of trees in m<sup>3</sup> per year, (e) cooling by transpiration in summer (kWh), and (f) cooling by shading in summer (kWh).

revealed clear geographical patterns in ESS provision. We identified regions within the city with lower ESS levels, similarly to Zięba-Kulawik et al. (2021). Our study further explored how land ownership influences ESS, a topic also discussed in other studies (e.g., Chambers-Ostler et al., 2024; Cimburova and Berghauser Pont, 2021; Hutt-Taylor and Ziter, 2022), showing a significant contribution from private trees. However, unlike most prior work reliant on field-work tree inventories, our comprehensive remote-sensing based dataset offers a valuable alternative, less time- and cost-intensive, complementary data source.

While our case study is based in Munich, the methods and insights are broadly applicable. The integration of multi-source, high-resolution data for ESS modeling at individual tree level contributes to urban ecological research and can inform comparable studies in cities worldwide, especially in those facing data limitations. However, the limited number of studies on this topic indicates that it is still an under-researched area, highlighting the need for further investigation and methodological development.

#### 4.1. Spatial distribution of ESS

A major contribution of our approach is the ability to integrate spatial detail into ESS assessment. Remote sensing enabled both individual tree-level analysis and spatial mapping of ESS across the study area. The ESS density maps showed consistent spatial patterns, reflecting the differences in built density and amount of green cover across the city.

Our spatial analysis (Fig. 2) shows hotspots and gaps in ESS provision. For example, *the Englischer Garten* and the areas along the Isar river, characterized by extensive tree cover and low levels of soil sealing, are major ESS hotspots. These areas have a large share of the city's carbon storage, offer strong cooling effects, and contribute to water balance regulation. On the other hand, densely built-up areas, like the old town and main train station, present very few or no trees and minimal ESS values. While these are, in general, foreseeable results, it renders them as plausible and the empirical proof allows for better knowledge-based

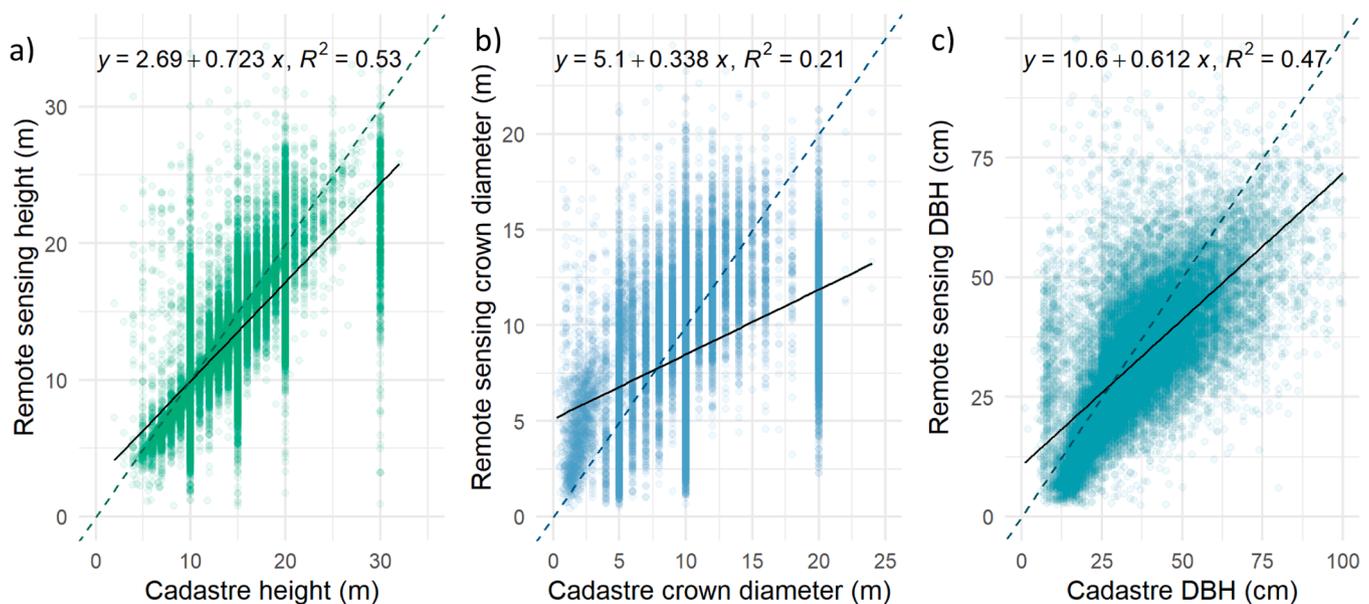


Fig. 5. Scatterplots showing the relationship between tree metrics recorded in the cadaster and the those estimated using remote sensing or statistical methods. (a) tree height, (b) crown diameter, and (c) diameter at the breast height (dbh). The dotted line represents the 1:1 relationship and the black solid lines correspond to the respective linear models.

management decisions at very high spatial resolution.

The overall trend shows that the core urban ESS are concentrated in large, open areas with large shares of vegetation such as parks. This highlights the importance of preserving or creating green corridors and urban parks for maintaining ecological functionality in cities. Trees in parks present ESS values approaching the upper limit. However, street trees also show a notable contribution, extending the spatial reach of ESS. Smaller tree clusters and isolated trees within building blocks, although contributing less individually, remain valuable for bringing ESS to densely built-up areas where larger green spaces are not feasible.

It is important to mention that the similar spatial patterns among different ESS may be partly derived from their shared reliance on the same tree characteristics, especially crown diameter and height, as shown by the PCA. Therefore, we generated ESS efficiency maps that provide complementary insights into the distribution of ESS, highlighting where trees perform well independently to their size. High CO<sub>2</sub> sequestration efficiency in large green areas likely reflects favorable soil conditions and lower management intensity, allowing trees to allocate resources more effectively to growth and carbon uptake. The highly heterogeneous pattern of shading efficiency highlights the importance of structural attributes, such as crown shape and height. The general low efficiency for these ESS observed along long street suggests the influence of monocultures and environmental constraints that limit their per-unit performance, even when tree density is relatively high.

The consistent low runoff reduction by trees efficiency and transpiration observed in large parks aligns with the strong role of soil permeability and background evapotranspiration conditions. Permeable areas promote infiltration and therefore limit the additional runoff reduction attributable to trees, whereas trees in locations with a higher share of impervious surfaces may show higher relative transpiration efficiency when enough water is available. Together, these results demonstrate that efficiency metrics are valuable for identifying areas where structural, genera-related, or contextual factors influence ESS provision, offering actionable insights for urban forest management beyond tree density alone.

Having this information is important for strategic tree management in cities that has a bigger impact in ESS provision. It helps identify areas where trees and ESS are lacking and highlights zones that require conservation or improved management. Our findings emphasize that

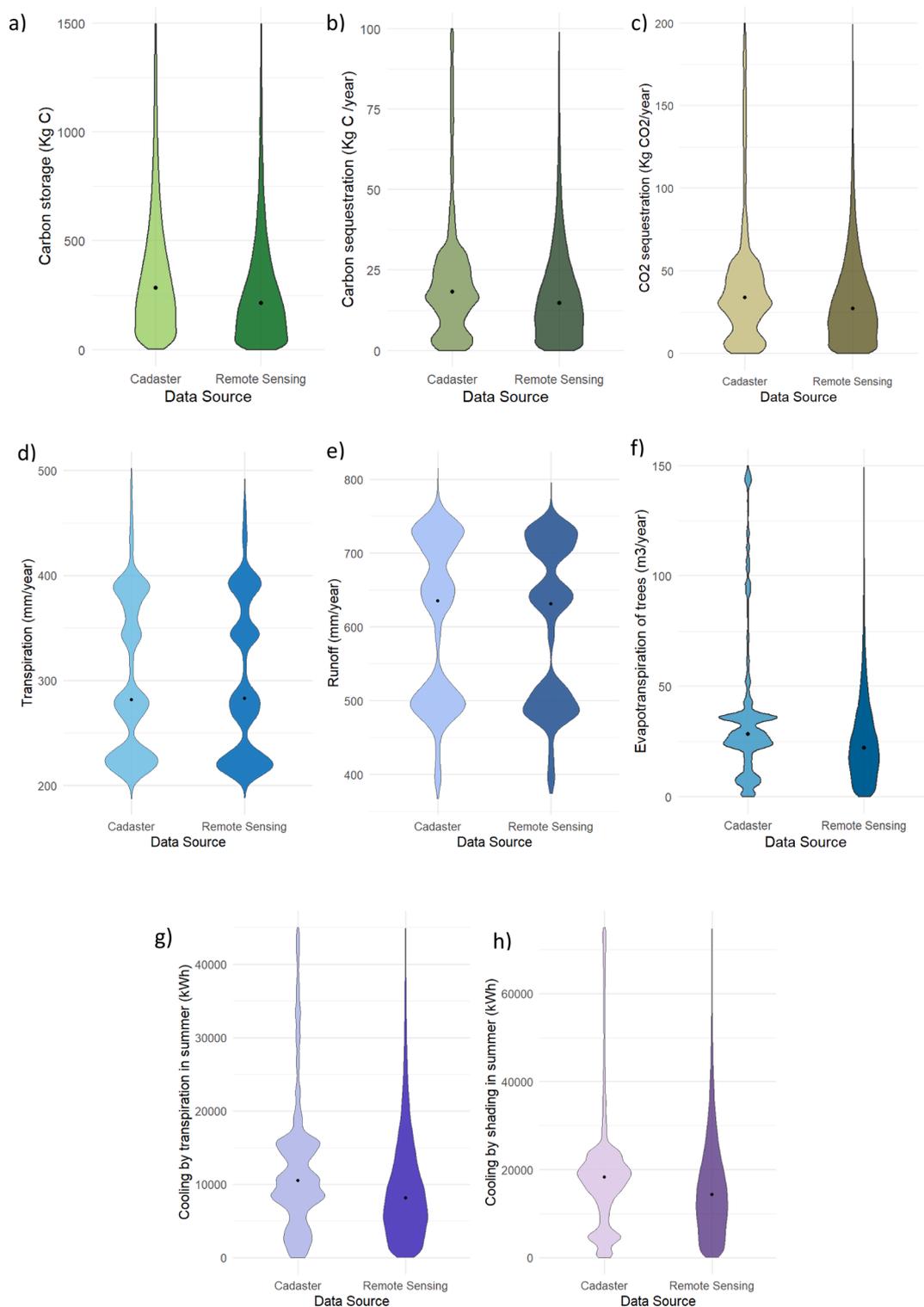
increasing ESS provision may require strategically targeted management interventions rather than simply increasing the number of trees. Moreover, spatial data makes ESS of urban trees measurable, visible, and actionable.

#### 4.2. Landownership comparison

Understanding the role of landownership in urban tree ESS is essential for two main reasons: First, different landownership classes are associated with different governance structures and management practices. These differences influence tree planting strategies, maintenance intensity, landscape development, and ultimately the magnitude of ESS provision (Jansson et al., 2019). Second, the municipal authorities typically have direct control only over public areas. In previous studies, trees located on private land are often underrepresented or entirely missing in the analyses as these data are often not included in official urban tree inventories (Hutt-Taylor and Ziter, 2022). We address this gap by using remote sensing to characterize trees across both public and private land, estimating the ESS potentially overlooked when relying solely on cadastral data. Our analysis using Munich as an example shows that at least a third of all ESS are generated by trees on private land, indicating that ESS estimates without comprehensive data are a distortion of reality. Additionally, we analyze how management regimes and structural characteristics of public trees (trees in parks and street trees) influence ESS provision.

In total, 54% of trees were classified as private and 46% as public. Among public trees, 26.1% were classified in recreational and 19.8% in traffic areas. We acknowledge that while using land use as a proxy for landownership is a practical proxy, it also introduces some inaccuracies, considering that land use does not always perfectly correspond to ownership boundaries or management regimes. Mixed-use areas, for example, may host a combination of public and private trees, which is not explicitly captured in our classification.

We found that private trees tend to be smaller and younger, as indicated by a right-skewed distribution in all structural metrics from Fig. 3. This likely results from tree replacement, pruning, and spatial limitations in some private yards. Street trees are generally medium-sized and show evidence of crown restrictions, probably due to pruning, unfavorable soil or other environmental conditions, and limited



**Fig. 6.** Comparison of urban trees' ecosystem services estimated using cadaster data and remote sensing data. The boxplots illustrate the distribution of values, with the central black point representing the median. a) Carbon storage in kg of carbon, (b) carbon sequestration in kg C per year, (c) CO<sub>2</sub> sequestration in kg/year, (d) transpiration in mm/year, (e) runoff in mm/year, (f) evapotranspiration of trees in m<sup>3</sup> per year, (g) cooling by transpiration in summer (kWh), and (h) cooling by shading in summer (kWh).

space. Recreational areas present larger trees with wider crowns, likely reflecting older trees, low management intensity, and favorable growing conditions such as low soil sealing. These differences confirm that tree parameters vary significantly across ownership classes and a uniform assumption would overlook this variability. However, we must consider that the complexity of the segmentation in areas with high tree density

could slightly influence crown size in recreational areas.

When comparing total ESS provision (Fig. 4), public trees contribute more than private trees to all ESS. Although they are less than half of the trees, public trees contribute over 57% to the ESS. This is particularly due to the high ESS values provided by trees in parks and woodland that typically feature larger, older trees in permeable soils and open settings,

**Table 2**  
Statistical comparison between remote sensing-derived and cadaster-derived ESS estimates.

| Ecosystem service  | Cohen's d | Welch's <i>t</i> -test |
|--|-----------|------------------------|
| Carbon storage (Kg C)                                    | 0.28      | 2.2e-16                |
| Carbon sequestration (Kg C/year)                         | 0.40      | 2.2e-16                |
| CO <sub>2</sub> sequestration (Kg CO <sub>2</sub> /year) | 0.40      | 2.2e-16                |
| Transpiration (mm/year)                                  | 0.02      | 0.004546               |
| Runoff (mm/year)   | 0.05      | 3.298e-09              |
| Evapotranspiration of trees (m <sup>3</sup> /year)       | 0.43      | 2.2e-16                |
| Cooling by transpiration in summer (kWh)                 | 0.43      | 2.2e-16                |
| Cooling by shading in summer kWh                         | 0.44      | 2.2e-16                |

which increases ESS provision. This highlights the strategic value of protecting and investing in these urban green spaces. In contrast, street trees contribute less to ESS. They represent just under 20% of all trees, and their potential is limited by smaller sizes, higher soil sealing, and species restrictions and pruning. This resembles what was found by Ferretti et al. (2025) regarding the less favorable conditions of streets trees for ESS provision. Still, their role should not be overlooked, especially where space is limited.

Private trees contribute less overall, mainly due to their smaller size, younger age, and more intensive management. Still, they account for over 36% of ESS, an important and often overlooked share. As many of these trees are still maturing, their future ESS potential is also promising. It is worth noting that our method currently only recognizes five tree genera, introducing uncertainty, especially since private grounds often host a wide variety of species that are likely being misclassified or generalized by our approach.

#### 4.3. Comparison of data sources

The last part of our analysis compares remote sensing-based estimations with the official tree cadaster. Cadaster data is often understood as ground truth and used for validation. However, in practice, it contains approximations, including rounded measurements. For instance, according to the measurement guidelines from Landeshauptstadt München (n.d.), tree positions in the cadaster have an accuracy of  $\pm 0.5$  m, and values for stem circumference, height, and crown diameter are typically rounded to standard values. On the other hand, remote sensing provides geometric measurements from photogrammetric and spectral techniques, which have their own limitations, especially in crown delineation for small or densely grouped trees.

As shown in Fig. 5, remote sensing slightly overestimates metrics of small trees and underestimated the metrics of larger trees. These differences might be related to crown delineation challenges or errors in the matching process. Additionally, the vertical clusters in cadaster data (Figs. 5a and 5b) also suggest the impact of field-based rounding. Interestingly, photogrammetrically derived tree heights may offer more precision than field-estimated values due to uncertainties in detecting the treetop, among other human errors.

Despite differences in tree metrics, Fig. 6 shows that ESS patterns are comparable between datasets. Cadaster-based ESS distributions tend to be multimodal, likely reflecting the influence of the rounded tree metrics, while remote sensing-based data produces smoother, right-skewed distributions. Runoff under the tree and transpiration show similar patterns and medians in both datasets, suggesting these ESS are more influenced by soil and climate than by tree measurement input.

Overall, it was found that the spatial patterns and overall trends are also closely aligned across datasets. Statistical tests (Cohen's *d* and Welch's *t*-test) show significant differences ( $p < 0.001$ ), but effect sizes are small to moderate, implying limited practical impact. While these results confirm that both datasets might be used comparably, it also shows that each has inherent biases and advantages. Cadaster provides detailed taxonomic and dbh precision, while remote sensing offers large-scale, consistent measurements. Rather than treating one as the

definitive reference, we suggest a complementary approach that leverages the advantages of both.

#### 4.4. Limitations

We acknowledge several limitations of our approach that may have affected the accuracy and generalizability of our results. First, the identification of tree species is restricted by the resolution and type of remote sensing data available. Therefore, not all existing species could be reliably detected or classified, potentially influencing the precision of ESS estimates, particularly those sensitive to species-specific parameters such as transpiration or carbon storage. Second, while the CityTree model relies on detailed structural attributes of individual trees, errors in the estimation of tree metrics, especially crown diameter, were frequent in dense or overlapping canopies, such as parks. This can lead to under- or overestimation of ESS in these areas. The inaccuracies of both methods propagate through the CityTree model and can impact the final ESS values. While large-scale patterns remain robust, we need to be careful when interpreting results at the individual tree level.

Additionally, the soil sealing index used as an input to the model is not based on high-resolution or standardized local measurements. This limits its robustness and may introduce uncertainty into ESS components that are sensitive to ground permeability, such as runoff. Furthermore, ground truth data might not be available in this context, as both measurement methods, i.e. remote sensing and in-situ have their own limitations and generalizations. Thus, absolute validation in quantitative form is not feasible, but similar trends from both data sets indicate the plausibility of the approaches. Despite these limitations, our approach provides valuable large-scale insights and highlights the potential of remote sensing for supporting spatially explicit urban tree ESS assessment.

Regarding the model, crown volume is simulated using species-specific allometric relationships derived from in-situ urban tree measurements (Franceschi et al., 2022). However, the lack of explicit information on individual pruning regimes introduces uncertainty at the tree level, which is inherent to large-scale urban ESS assessments. We also acknowledge that cooling by trees may also constitute a disservice in winter by reducing solar radiation and potentially increasing buildings' heating demand. These effects depend strongly on tree location relative to buildings (Reitberger et al., 2025). Such building-specific interactions are not represented in the CityTree model and were therefore not considered in this study. Our cooling estimates should be interpreted as seasonal (summer) benefits related to outdoor thermal regulation, rather than net annual energy effects.

#### 4.5. Future work

There is potential to improve our approach and expand its applications. A more robust soil sealing analysis is needed to improve the water balance simulations. Additionally, future research is suggested to explore the scalability of these methods to other cities, which could also enable comparative studies across cities and regions. The dataset we generated also opens opportunities for interdisciplinary research, such as examining environmental justice and inequalities in urban ESS distribution across neighborhoods (cf. Weigand et al., 2023). When combined with demographic, socio-economic, or public health data, this information could support more equitable urban green planning (Ponette-González et al., 2025).

## 5. Conclusion

Our findings demonstrate that remote sensing has strong potential to support city-wide, individual-tree ESS modelling for individual trees in an area-wide and consistent manner. First, by integrating optical remote sensing data with the CityTree model, we successfully mapped multiple ESS at the individual-tree level across 44 km<sup>2</sup> in Munich, Germany. The

resulting spatial patterns highlight the heterogeneity in ESS provision, driven not only by tree density but also by structural characteristics and local environmental conditions.

Second, the comprehensive coverage provided by remote sensing allowed an area-wide analysis of ESS provision across land ownership types. Our results showed that public trees, especially those in recreational areas, provide the majority of ESS. Private trees also make a large contribution, accounting for at least one third of the total ESS. This finding confirms that excluding private trees from urban tree inventories leads to a systematic underestimation of ESS.

Finally, the comparison between remote sensing-derived and cadaster-based ESS estimates revealed consistent spatial patterns and trends, despite differences in absolute values. These differences can largely be attributed to measurement rounding in field data and segmentation errors and misclassification of species in remote sensing. Overall, our findings suggest that remote sensing can reproduce ESS patterns while overcoming spatial gaps inherent in field-collected datasets. Remote sensing emerges as a robust and cost-effective complementary data source for large-scale urban tree ESS assessment.

### CRedit authorship contribution statement

**Andrea Sofía García de León:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas Rötzer:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Tobias Leichte:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Tobias Ullmann:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Hannes Taubenböck:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Stephan Pauleit:** Writing – review & editing, Supervision, Methodology, Conceptualization. **John Friesen:** Writing – review & editing, Supervision, Methodology. **Klaus Martin:** Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT to improve readability of some paragraphs. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

### Funding

This work was funded by the German Federal Environmental Foundation -DBU- (project 37076/01). Further, the Free State of Bavaria funded this research via the Bavarian State Ministry of Economic Affairs, Regional Development and Energy and the German Aerospace Center (DLR) as part of the “Earth Observation Innovation Laboratory for Climate Adaptation and Mitigation” project ([www.EO4CAM.de](http://www.EO4CAM.de)).

### Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given his role as part of the editorial board, Stephan Pauleit had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

We would like to thank European Space Imaging (EUSI) for providing the WorldView data used in this study. Additionally, we would like to thank the City of Munich for supplying the tree cadaster, the orthophotos, and the normalized Digital Surface Model.

### References

- Alvarado, O., 2025. Quantifying ecosystem services from trees of an urban park in Amsterdam. *Water Int* 1–32. <https://doi.org/10.1080/02508060.2025.2468586>.
- Aram, F., Higuera García, E., Solgi, E., Mansournia, S., 2019. Urban green space cooling effect in cities. *Heliyon* 5, e01339. <https://doi.org/10.1016/j.heliyon.2019.e01339>.
- ATKIS, 2023. Tatsächliche Nutzung (TN).
- Baines, O., Wilkes, P., Disney, M., 2020. Quantifying urban forest structure with open-access remote sensing data sets. *Urban For. Urban Green.* 50, 126653. <https://doi.org/10.1016/j.ufug.2020.126653>.
- Barbier, E.B., 2013. Economics of the Regulating Services. In: *Encyclopedia of Biodiversity*. Elsevier, pp. 45–54. <https://doi.org/10.1016/B978-0-12-384719-5.00183-0>.
- Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* 5, 180214. <https://doi.org/10.1038/sdata.2018.214>.
- Berland, A., Shiflett, S.A., Shuster, W.D., Garmestani, A.S., Goddard, H.C., Hopton, M.E., Herrmann, D.L., 2017. The role of trees in urban stormwater management. *Landsc. Urban Plan.* 162, 167–177. <https://doi.org/10.1016/j.landurbplan.2017.02.017>.
- Böhner, J., Antonić, O., 2009. Chapter 8 Land-Surface Parameters Specific to Topo-Climatology. in: *Developments in Soil Science*. Elsevier, pp. 195–226. [https://doi.org/10.1016/S0166-2481\(08\)00008-1](https://doi.org/10.1016/S0166-2481(08)00008-1).
- Carlyle-Moses, D.E., Livesley, S., Baptista, M.D., Thom, J., Szota, C., 2020. Urban Trees as Green Infrastructure for Stormwater Mitigation and Use. In: *Levia, D.F., Carlyle-Moses, D.E., Iida, S., Michalzik, B., Nanko, K., Tischer, A. (Eds.), Forest-Water Interactions, Ecological Studies*. Springer International Publishing, Cham, pp. 397–432. [https://doi.org/10.1007/978-3-030-26086-6\\_17](https://doi.org/10.1007/978-3-030-26086-6_17).
- Centre for Urban Ecology and Climate Adaptation-TUM, 2024a. *Clim. a CityMunich* [WWW Doc.]. City URL (<https://master.d3jwj4w13tyob.amplifyapp.com/info?type=e=city>) (accessed 5.11.24).
- Centre for Urban Ecology and Climate Adaptation-TUM, 2024b. *Soil Type* [WWW Doc.]. Soil Type URL ([https://master.d3jwj4w13tyob.amplifyapp.com/info?type=soil\\_type](https://master.d3jwj4w13tyob.amplifyapp.com/info?type=soil_type)) (accessed 5.20.25).
- Chambers-Ostler, A., Walker, H., Doick, K.J., 2024. The role of the private tree in bringing diversity and resilience to the urban forest. *Urban For. Urban Green.* 91, 127973. <https://doi.org/10.1016/j.ufug.2023.127973>.
- Chen, W.Y., 2015. The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: A nationwide estimate. *Cities* 44, 112–120. <https://doi.org/10.1016/j.cities.2015.01.005>.
- Cimburowa, Z., Barton, D.N., 2020. The potential of geospatial analysis and Bayesian networks to enable i-Tree Eco assessment of existing tree inventories. *Urban For. Urban Green.* 55, 126801. <https://doi.org/10.1016/j.ufug.2020.126801>.
- Cimburowa, Z., Berghauer Pont, M., 2021. Location matters. A systematic review of spatial contextual factors mediating ecosystem services of urban trees. *Ecosyst. Serv.* 50, 101296. <https://doi.org/10.1016/j.ecoser.2021.101296>.
- Cohen, J., 1988. *Statistical Power Analysis for the Behavioral Sciences*, 0 ed. Routledge. <https://doi.org/10.4324/9780203771587>.
- d'Angelo, P., Kurz, F., 2019. Aircraft based real time bundle adjustment and digital surface model generation. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLII-2/W13*, 1643–1647. <https://doi.org/10.5194/isprs-archives-XLII-2-W13-1643-2019>.
- DWD Climate Data Center, 2025. *Climate Munich-City*.
- Fang, F., McNeil, B.E., Warner, T.A., Maxwell, A.E., Dahle, G.A., Eutsler, E., Li, J., 2020. Discriminating tree species at different taxonomic levels using multi-temporal WorldView-3 imagery in Washington D.C., USA. *Remote Sens. Environ.* 246, 111811. <https://doi.org/10.1016/j.rse.2020.111811>.
- Ferretti, E., Soares, A.L., Nunes, L., Duarte, I.M., Dias, S., 2025. Contribution of urban trees to ecosystem services in Lisbon: a comparative study between gardens and street trees. *Arboric. Urban For., jauf.* 2025.013 <https://doi.org/10.48044/jauf.2025.013>.
- Franceschi, E., Moser-Reischl, A., Rahman, M.A., Pauleit, S., Pretzsch, H., Rötzer, T., 2022. Crown shapes of urban trees-their dependences on tree species, tree age and local environment, and effects on ecosystem services. *Forests* 13 (5), 748. <https://doi.org/10.3390/f13050748>.
- García de León, A.S., Leichte, T., Droin, A., Rieder, J., Castañeda-Gómez, A., Rötzer, T., Martin, K., Ullmann, T., Taubenböck, H., 2025. How can remote sensing support urban tree cadaster efforts and tree genus diversity analysis? *Manuscr. Submitt. Publ.*
- García-Pardo, K.A., Moreno-Rangel, D., Domínguez-Amarillo, S., García-Chávez, J.R., 2022. Remote sensing for the assessment of ecosystem services provided by urban vegetation: a review of the methods applied. *Urban For. Urban Green.* 74, 127636. <https://doi.org/10.1016/j.ufug.2022.127636>.
- Guo, J., Xu, Q., Zeng, Y., Liu, Z., Zhu, X.X., 2023. Nationwide urban tree canopy mapping and coverage assessment in Brazil from high-resolution remote sensing images using deep learning. *ISPRS J. Photogramm. Remote Sens.* 198, 1–15. <https://doi.org/10.1016/j.isprsjprs.2023.02.007>.

- Hanna, E., Bruno, D., Comín, F.A., 2024. The ecosystem services supplied by urban green infrastructure depend on their naturalness, functionality and imperviousness. *Urban Ecosyst.* 27, 187–202. <https://doi.org/10.1007/s11252-023-01442-9>.
- Hao, T., Zhao, Q., Huang, J., 2023. Optimization of tree locations to reduce human heat stress in an urban park. *Urban For. Urban Green.* 86, 128017. <https://doi.org/10.1016/j.ufug.2023.128017>.
- 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>.
- Jansson, M., Vogel, N., Fors, H., Randrup, T.B., 2019. The governance of landscape management: New approaches to urban open space development. *Landsc. Res.* 44 (8), 952–965. <https://doi.org/10.1080/01426397.2018.1536199>.
- Landeshauptstadt München, n.d. Terrestrisches Aufmaß für Bäume in städtischen Grünflächen innerhalb des Mittleren Rings – Gebiet 1. Munich.
- Lee, J.-H., Ko, Y., McPherson, E.G., 2016. The feasibility of remotely sensed data to estimate urban tree dimensions and biomass. *Urban For. Urban Green.* 16, 208–220. <https://doi.org/10.1016/j.ufug.2016.02.010>.
- Leichtle, T., Zehner, M., Kühnl, M., Martin, K., Taubenböck, H., 2021. Urban Trees – Detection, Delineation, Quantification, and Characterisation based on VHR Remote Sensing. In: REAL CORP 2021: CITIES 20.50. Creating Habitats for the 3rd Millennium: Smart - Sustainable - Climate Neutral. Presented at the 26th International Conference on Urban Planning. Regional Development and Information Society, Vienna, Austria.
- Livesley, S.J., McPherson, E.G., Calafapietra, C., 2016. The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. *J. Environ. Qual.* 45, 119–124. <https://doi.org/10.2134/jeq2015.11.0567>.
- MEA, 2005. *Ecosystems and Human Well-being: Wetlands and Water Synthesis*. World Resources Institute, Washington, DC.
- Mengist, W., Soromessa, T., Feyisa, G.L., 2020. A global view of regulatory ecosystem services: existed knowledge, trends, and research gaps. *Ecol. Process.* 9, 40. <https://doi.org/10.1186/s13717-020-00241-w>.
- Mengxuan, J., 2025. *Structure and Growth of Common Tree Species in European Cities - An Allometric Analysis of Species Specific Structural Growth Patterns*. Technical University of Munich.
- Morgenroth, J., Buchan, G., 2009. Soil moisture and aeration beneath pervious and impervious pavements. *Arboric. Urban For.* 35, 135–141. <https://doi.org/10.48044/jauf.2009.024>.
- Moser-Reischl, A., Rötzer, T., Pauleit, S., Pretzsch, H., 2021. Urban tree growth characteristics of four common species in South Germany. *Arboric. Urban For.* 47, 150–169. <https://doi.org/10.48044/jauf.2021.015>.
- Nowak, D., Crane, D.E., 2000. The Urban Forest Effects (UFORE) model: quantifying urban forest structure and function. *Integr. Tools Nat. Resour. Invent. 21st Century*.
- Nowak, D., Walton, J., Stevens, J., Crane, D., Hoehn, R., 2008. Effect of plot and sample size on timing and precision of urban forest assessments. *Arboric. Urban For.* 34, 386–390. <https://doi.org/10.48044/jauf.2008.052>.
- Nowak, D.J., Maco, S., Binkley, M., 2018. i-Tree: global tools to assess tree benefits and risks to improve forest management. *Arboric. Consult.* 51.
- Pauleit, S., Gulsrud, N., Raum, S., Taubenböck, H., Leichtle, T., Erlwein, S., Rötzer, T., Rahman, M., Moser-Reischl, A., 2022. *Smart Urban Forestry: Is It the Future?* In: Chokhachian, A., Hensel, M.U., Perini, K. (Eds.), *Informed Urban Environments, The Urban Book Series*. Springer International Publishing, Cham, pp. 161–182. [https://doi.org/10.1007/978-3-031-03803-7\\_10](https://doi.org/10.1007/978-3-031-03803-7_10).
- Peng, L., Chen, S., Liu, Y., Wang, J., 2008. Application of CITYgreen model in benefit assessment of Nanjing urban green space in carbon fixation and runoff reduction. *Front. For. China* 3, 177–182. <https://doi.org/10.1007/s11461-008-0035-6>.
- Ponette-González, A.G., Fry, M., Hirschfeld, D., Rose, J., Elderbrock, E., 2025. Just distribution of tree canopy? A digital approach to tree equity. *J. Am. Plann. Assoc.* 1–9. <https://doi.org/10.1080/01944363.2025.2501610>.
- Pretzsch, H., Biber, P., Uhl, E., Dahlhausen, J., Rötzer, T., Caldentey, J., Koike, T., Van Con, T., Chavanne, A., Seifert, T., Toit, B.D., Farnden, C., Pauleit, S., 2015. Crown size and growing space requirement of common tree species in urban centres, parks, and forests. *Urban For. Urban Green.* 14, 466–479. <https://doi.org/10.1016/j.ufug.2015.04.006>.
- Rahman, M.A., Hartmann, C., Moser-Reischl, A., Von Strachwitz, M.F., Paeth, H., Pretzsch, H., Pauleit, S., Rötzer, T., 2020. Tree cooling effects and human thermal comfort under contrasting species and sites. *Agric. For. Meteorol.* 287, 107947. <https://doi.org/10.1016/j.agrformet.2020.107947>.
- Rahman, M.A., Moser, A., Rötzer, T., Pauleit, S., 2019. Comparing the transpirational and shading effects of two contrasting urban tree species. *Urban Ecosyst.* 22, 683–697. <https://doi.org/10.1007/s11252-019-00853-x>.
- Rahman, M.A., Stringer, P., Ennos, A.R., 2013. Effect of pit design and soil composition on performance of *Pyrus calleryana* street trees in the establishment period. *Arboric. Urban For.* 39. <https://doi.org/10.48044/jauf.2013.033>.
- Reitberger, R., Leichtle, T., Palm, H., Deghim, F., Rempfer, C., Mutzhas, D., Lang, W., 2025. Impact of trees on the heating energy demand of buildings: statistical investigation with in situ and earth observation data. *J. Phys. Conf. Ser.* 3140 (6), 062011. <https://doi.org/10.1088/1742-6596/3140/6/062011>.
- Rötzer, T., Franceschi, E., Reischl, A., Rahman, M., Bradatsch, M., Pretzsch, H., Pauleit, S., 2024. *Leitfaden Stadtbäume im Klimawandel. Zweite erweiterte Aufl. Des. Leitf. zu Stadtb. äumen Bayern*.
- Rötzer, T., Moser-Reischl, A., Rahman, M.A., Grote, R., Pauleit, S., Pretzsch, H., 2020. Modelling Urban Tree Growth and Ecosystem Services: Review and Perspectives. In: Cánovas, Lüttge, F.M., Risueno, U., Pretzsch, Hans, M.-C. (Eds.), *Progress in Botany* Vol. 82. Springer International Publishing, Cham, pp. 405–464. [https://doi.org/10.1007/124\\_2020\\_46](https://doi.org/10.1007/124_2020_46).
- Rötzer, T., Rahman, M.A., Moser-Reischl, A., Pauleit, S., Pretzsch, H., 2019. Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions. *Sci. Total Environ.* 676, 651–664. <https://doi.org/10.1016/j.scitotenv.2019.04.235>.
- Shahtahmassebi, A.R., Li, C., Fan, Y., Wu, Y., Lin, Y., Gan, M., Wang, K., Malik, A., Blackburn, G.A., 2021. Remote sensing of urban green spaces: a review. *Urban For. Urban Green.* 57, 126946. <https://doi.org/10.1016/j.ufug.2020.126946>.
- Sharma, G., Morgenroth, J., Richards, D.R., Ye, N., 2025. Advancing urban forest and ecosystem service assessment through the integration of remote sensing and i-Tree Eco: a systematic review. *Urban For. Urban Green.* 104, 128659. <https://doi.org/10.1016/j.ufug.2024.128659>.
- Sharma, R., Bakshi, B.R., Ramteke, M., Kodamana, H., 2024. Quantifying ecosystem services from trees by using i-tree with low-resolution satellite images. *Ecosyst. Serv.* 67, 101611. <https://doi.org/10.1016/j.ecoser.2024.101611>.
- Song, P., Kim, G., Mayer, A., He, R., Tian, G., 2020. Assessing the ecosystem services of various types of urban green spaces based on i-Tree Eco. *Sustainability* 12, 1630. <https://doi.org/10.3390/su12041630>.
- 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>.
- Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and flow: a conceptual framework for analyzing ecosystem service provision and delivery. *Ecol. Complex.* 15, 114–121. <https://doi.org/10.1016/j.ecocom.2013.07.004>.
- Wallace, L., Sun, Q. (Chayn), Hally, B., Hillman, S., Both, A., Hurley, J., Martin Saldias, D.S., 2021. Linking urban tree inventories to remote sensing data for individual tree mapping. *Urban For. Urban Green.* 61, 127106. <https://doi.org/10.1016/j.ufug.2021.127106>.
- 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). <https://doi.org/10.1080/10106049.2023.2286305>.
- Welch, B.L., 1947. The generalization of “Student’s” problem when several different population variances are involved. *Biometrika* 34, 28–35.
- Zięba-Kuławik, K., Hawryło, P., Wężyk, P., Matczak, P., Przewoźna, P., Ingłot, A., Mączka, K., 2021. Improving methods to calculate the loss of ecosystem services provided by urban trees using LiDAR and aerial orthophotos. *Urban For. Urban Green.* 63, 127195. <https://doi.org/10.1016/j.ufug.2021.127195>.