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# Urban Trees – Detection, Delineation, Quantification, and Characterisation based on VHR Remote Sensing

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## 1 ABSTRACT

Trees play a vital role in the urban ecosystem, providing benefits for society, ecology and economy. In particular in urban areas, trees mitigate the urban heat island effect, filter air pollution, regulate microclimate and hydrology, bond carbon dioxide, and provide spaces for recreation and leisure, among others. Despite these diverse positive effects, detailed information on the number, location, dimensions and other characteristics of urban trees remains scarce. For this reason, most cities in Germany currently aim to establish a tree information system for efficient and targeted management of their tree inventory. However, traditional terrestrial surveying is time-consuming and costly and therefore only suitable to a limited extent. In addition, the municipal tree cadastre usually only includes urban trees on public propertyand thus does not cover the complete stock. Against this background, remote sensing acquisitions with very-high spatial resolution (VHR) of less than one meter offer promising capabilities for area-wide detection, delineation, and characterization of urban trees.

In this study, we use VHR aerial imagery as well as a derived canopy height model (CHM) for detection and delineation of urban trees. Different methods for individual tree detection using local maximum (LM) filtering andLaplacian of Gaussian (LoG) blob detectionare compared and evaluated. For tree crown delineation, marker-controlled watershed segmentation (MCWS), clustering using Voronoi tessellation, and region growing are implemented as segmentationtechniques. The detection of individual trees and delieation of tree crowns are validated against about1,000 reference trees from visual interpretation via stereophotogrammetry.In addition, we relate our results to street tree location data of Munich, which was derived from mobile terrestrial laser scanning (TLS).The characterization of urban trees is realized based on the 3-dimensional shape of individual tree segments as well as auxillary data sets of land use and building density.

According to our analyses, there are 1.54 million trees in Munich.Compared to available reference trees, tree detection was evaluated with highest values of F-score, precision, and recall of 0.95, 0.99, and 0.94, respectively. Results of tree crown segmentation revealed an overall accuracy of 88.1 % compared to crowns of reference trees. Based on auxillary land use information, urban trees were categorized into street trees, (public) park trees, as well as trees in (private) residential gardens.In Munich, 9.1 % are characterized as street trees, 38.4 % are allocated in residential gardens and 33.1 % stand in public parks. The remaining 19.4 % oftree segments were found onother land use such as agricultural areas, parking lots, or along railroad tracks. According to these categories, the height and crown area of urban trees are analyzed and related to the distance to the city center. In a more general manner, this analysis was performed in relation to the building density in Munich. As expected, relatively few trees were found close to the city center and generally on areas with high building density. However, these areas are particularly associated with the greatest challenges in the context of sustainable and climate change-adapted urban development.In this study, we demonstrate that information derived from remote sensing contributes new spatial and quantitative knowledge on urban trees, providing the basis for sustainable management and informed decision-making in cities.

Keywords: characterization, very-high spatial resolution (VHR), urban trees, remote sensing, urban ecosystem

## 2 INTRODUCTION

Urban trees are highly relevant to the urban ecosystem and offer suitable capabilities to compensate for the negative consequences of urbanization and climate change(Pauleit, Zölch, Reischl, Rahman, & Rötzer, 2019). Particularly in urban areas, trees mitigate the urban heat island effect through evapotranspiration and shade, reduce surface water runoff, filter air pollution, and absorb carbon dioxide, among others(Rötzer, et al., 2020). In addition, trees provide city dwellers with space for recreation and leisure and have a positive effect on health in many ways(Taubenböck, et al., 2020).The great importance of urban green for people's well-being also became especially evident during the global COVID-19 pandemic (Grima, et al., 2020). Urban trees, also referred to as "Urban Forest" as a whole, include trees in parks, forests, on (private) residential areas, on squares and along streets, as well as greenbelt vegetation (Miller, Hauer, & Werner, 2015). Compared to forest trees, urban trees are exposed to diverse and mostly negative environmental influences at their growing sites which vary strongly within and across cities(Rötzer, et al., 2020). Thus, their structural development as well as associated ecosystem services are diverse and require consistent area-wide and up-to-date informationas a basis for efficient, targeted, as well as sustainable managementand informed decision-making in cities.

Traditional terrestrial surveying of urban trees is time-consuming and costly.For this reason, inventories of individual trees are scarce and often not publicly available (Kronenberg, Łaszkiewicz, & Sziło, 2021). This is also the case inthe city of Munich: no area-wide urban tree cadastre is available to date. In addition, municipal data bases target public spaces, whereas urban trees on private properties are omitted despite their equally important functions and ecosystem services. Remote sensing has proven suitable capabilities for area-wide assessment of land cover, also regarding vegetation and trees in cities(Tigges, Lakes, & Hostert, 2013; Taubenböck, et al., 2021). Especially acquisitions with very-high spatial resolution (VHR) of less than one meter offer promising capabilities for area-wide detection, delineation, and characterization of urban trees(Shojanoori & Shafri, 2016).Existing research on individual tree detection and crown delineation (ITCD) focuses on forest areas, whereas less than one tenth of all studies aim to capture treeswithin urban areas (Zhen, Quackenbush, & Zhang, 2016).Specific challenges for ITCD in urban areas are the complex and small-scale heterogeneous composition of land cover accompanied by diverse dimensions and structure of urban trees(Zhang, Zhou, & Qiu, 2015). The dominant source of remote sensing data for ITCD is a raster-based digital surface model (DSM) or canopy height model (CHM), which can be delineated from active LiDAR (light detection and ranging) acquisitions or passive stereophotogrammetry(Ke & Quackenbush, 2011).In general, leaf-on data is preffered over leaf-off data for ITCD, since detection and delineation of trees especially in urban areas requires masking of trees against other land coveras a preprocessing step (Zhang & Hu, 2012).Several methodological approaches have been proposed for tree detection, including local maximum (LM) filtering (e.g., (Pouliot, King, Bell, & Pitt, 2002), (Wang, Gong, & Biging, 2004)), scale-space functions (e.g., (Wagner, et al., 2018)), or template matching (e.g. (Vahidi, Klinkenberg, Johnson, Moskal, & Yan, 2018)), among others. Algorithms for tree crown delineation comprise valley following (e.g., (Gougeon, 1999)), region growing (e.g., (Pouliot, King, Bell, & Pitt, 2002), (Dalponte & Coomes, 2016)), or marker-controlled watershed segmentation(MCWS) (e.g., (Wang, Gong, & Biging, 2004), (Silva, et al., 2016)).Additional methods for tree crown segmentation are realized based on object-based image analysis (OBIA) (e.g., (Ardila, Bijker, Tolpekin, & Stein, 2012)) or recently emerging deep learning techniques (e.g., (Weinstein, et al., 2020)).

In this study, leaf-on VHR aerial imagery as well as its derived CHM are used as data basis for ITCD. We evaluate LM filtering and Laplacian of Gaussian (LoG) blob detection for individual tree detectionand compare MCWS, clustering using Voronoi tessellation (CL), and region growing (RG)for tree crown delineation. Validation is conducted based on 952 reference trees from visual stereo image interpretation as well asin relation to street tree location data of Munichderived from mobile terrestrial laser scanning (TLS). Finally, the 3-dimensional shape of individual tree segments as well as land use and building density are employed for characterization of urban trees in the city of Munich.

## 3 STUDY AREA & DATA

The study area is the city of Munich, which covers an administrative area of 310 km² (Figure 1). Recent analyses of the German Meteorological Service (DWD) revealedan increasing count of warm days, a decreaseing number of frost days and higher mean annual temperatures during the last decades. These observations are seenas a indicationsof climate change effects(Mühlbacher, Koßmann, Sedlmeier, & Winderlich, 2020). A recent study of Munich suggests that local heat stress can be reduced most efficiently by strategically planted trees (Zölch, Maderspacher, Wamsler, & Pauleit, 2016).

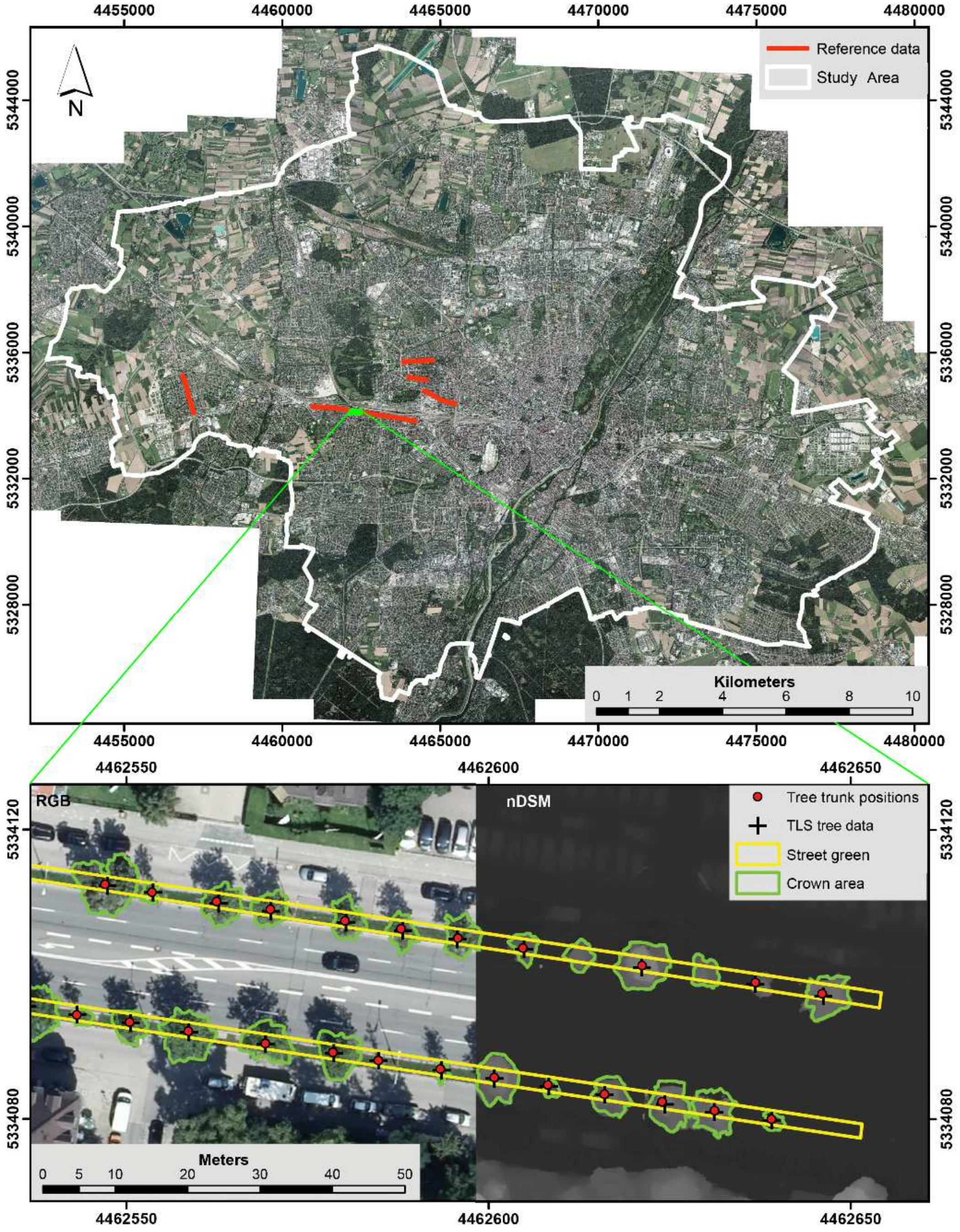


Figure 1: Study area corresponding to the administrative area of Munich, and detailed view of remote sensing as well as reference data. Aerial imagery is provided by Geobasisdaten© Landeshauptstadt München - Kommunalreferat -GeodatenService 2021.

VHR aerial acquisitions were recorded under leaf-on conditions in August 2017 as well as during the leaf-off period in February 2019 using the UltraCam Xp-1 with ground resolution of 10 cm (provided by Geobasisdaten © Landeshauptstadt München - Kommunalreferat -GeodatenService 2021). Multispectral imagery is available from these acquisitions as RGBI data, while a DSM as well as a DTM were generated by means of stereophotogrammetry. Based on leaf-on as well as leaf-off aerial acquisitions, tree trunk positions as well as tree crowns of 952 reference trees were collected via visual interpretation of stereo imagery. All aerial imagery is available in the geometry of true orthophotos, i.e. without parallax distortions of vertical objects.Additional comparative data on tree positions are available from the street tree location data of Munich, which comprises tree trunk positions of 57,800 street trees derived from mobile TLS acquisition in September 2020. However, the accuracy of this data is unknown. Auxillary data comprises a


ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

street green layer from the city of Munich which holds all roadside vegetated areas (with and without trees), a landuse dataset which distinguishes parks, residential areas and transportation infrastructure, as well as building density data, which is provided on a 100x100m² polygon grid.

## 4 METHODOLOGY

A CHM is generated by subtracting the DTM from the DSM of the leaf-on aerial acquisitions.Subsequently, non-tree pixels are masked by thresholding height in the CHM as well as the normalized difference vegetation index (NDVI).In order to compensate very small-scale variations due to single tree branches in the aerial imagery as well as in the CHM, a Gaussian filter was applied (Brandtberg & Walter, 1998).Tree detection is performed based on the filtered CHM using LM filtering and LoG blob detection. LM filtering is chosen due to its popularity and high level of development (Zhen, Quackenbush, & Zhang, 2016). In order to account for different sizes of tree crowns, a height dependent linear variable window function was employed as a modification of the traditional LM filtering technique (Popescu & Wynne, 2004). LoG blob detection belongs to the category of scale-space functions and compares kernel regions from the CHM to Gaussian blobs in order to detect indivudal trees (Kaartinen, et al., 2012).For tree crown delineation, three segmentation approaches MCWS, CL, and RG are compared. The MCWS algorithm is widely used for tree crown segmentation and uses markers (i.e. treetop positions) for gradual watershed delineation of the inverted CHM (Wang, Gong, & Biging, 2004). CL creates height-dependent circular buffers around each marker in the CHM, whereas at intersecting buffers a Voronoi-tessellation is carried out (Silva, et al., 2016). Finally, RG starts at marker positions and merges surrounding pixels of the CHM dependent on thresholds for crown segment growth and maximum crown diameter (Dalponte & Coomes, 2016).For application of ITCD for the entire city of Munich, a two-staged approach was realized. First, area-wide ITCD aiming to capture large and medium sized trees was performed based on masking parameters of CHM height > 2 m and NDVI > 0.4 for the entire city area. Second, small roadside trees were added by restricting the area for ITCD to the auxillary street green layer with simultaneous relaxation of the masking parameters to CHM height > 1.3 m and NDVI > 0.3.

Validation of results was carried out according to the two steps of ITCD, tree detection and tree crown delineation. For each reference tree trunk position, the closest markerswithin each reference crown were identified from LM filtering as well as LoG blob detection and subsequently counted as true positives. Additional markers within reference tree crowns were counted as false positives, and missed trees (i.e. reference crowns without markers) as false negatives. Precision, recall, and the F-score were calculated as measures of tree detection performance(Li, Guo, Jakubowski, & Kelly, 2012). Tree crown delineation was evaluated according to the intersection over union (IoU) as a spatial measure of common overlap of reference against predicted tree crowns.Dependent on theIoU of reference and predicted crown segments, tree crownsare categorized as matched, nearly matched, missed, merged, or split; for details on the definitions of this accuracy assessment scheme see(Jing, Hu, Noland, & Li, 2012). The categories ofmatched and nearly matched tree crowns are related to all reference crowns for calculation of overall accuracy (OA).

## 5 RESULTS

### 5.1 Accuracies of tree detection and delineation

Figure 2 illustrates results of ITCD for a small subset of the study area of the city of Munich.From a visual point of view, LoG blob detection found too few markers compared to LM filtering in case of street trees, whereas LM filtering identified too many individual trees in groups of trees with overlapping crowns (top row of Figure 2). Quantitative accuracy assessment regarding tree detection is presented in Table 1. The numbers confirm the visual impression that LoG blob detection results in very few false positives (i.e. no overestimation of trees), while LM filtering possesses fewer false negatives (i.e. missed trees). Consequently, highest accuracies of precision were retrieved for LoG blob detection, whereas recall and F-scorewere found superior in case of LM filtering. This applies to both, the area-wide as well as the street green restricted approach.The detected treetop positions are spatially offset compared to tree trunk positions, with mean distance of 0.94 m for the area-wide, and 0.78 m for the street green restricted approach.

The three segmentation methods for tree crown delineation presented in the bottom row of Figure 2 visually show very similar results. In general, RG results in the relatively smallest crown segments, while MCWS draws the most expansive tree crowns.By comparison of the second and third column of Figure 2, the dependency of all segmentation procedures on the previously detected markers represents the greatest difference and is methodologically inherent due to the two steps of ITCD.

| | **Tree detection method** | **Precision** | **Recall** | **F-score** |
|---|---|---|---|---|
| Area-wide approach | LM filtering | 0.936 | 0.866 | 0.899 |
| | LoG blob detection | 0.984 | 0.770 | 0.864 |
| Restricted to street green | LM filtering | 0.959 | **0.939** | **0.949** |
| | LoG blob detection | **0.991** | 0.832 | 0.905 |

Table 1: Tree detection performance.

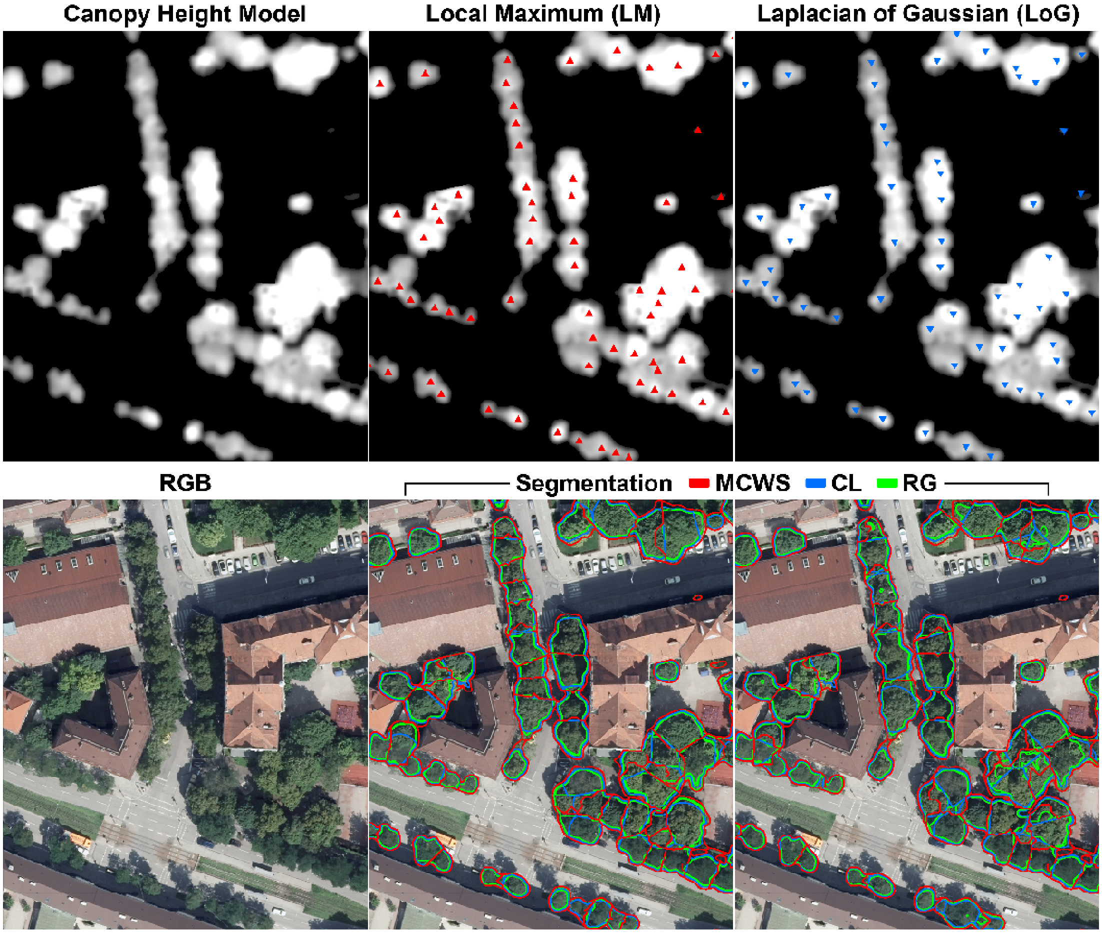


Figure 2: Results of tree detection (top row) and corresponding tree crown delineation (bottom row). Aerial imagery is provided by Geobasisdaten© Landeshauptstadt München - Kommunalreferat -GeodatenService 2021.

Figure 3 presents the relative distribution of categories from the IoU analysis of reference against predicted tree crowns for tree delineation performance assessment. In general and in accordance with tree detection, tree crown segmentation shows superior accuracy in case of the area restriction to the street green layer compared to the area-wide approach. In this regard, significantly less reference trees were missed (yellow category in Figure 3) compared to area-wide approach. The advantage of markers from LM filtering also becomes apparent with respect to all three segmentation methods. Comparing the three segmentation procedures, highest OA (i.e. share of matched and nearly matched crowns) of 76.6 and 88.1 % were retrieved by MCWS for the area-wide and the street green restricted approach, respectively.

An example of the relative comparison of the TLS data with ITCD based on the markers derived from LM filtering in combination with MCWS is depicted in Figure 4. 53,000 of the 57,800 tree positions from the TLS survey were located within delineated tree crowns which corresponds to an agreement of 91.7 %. On average, the distance of markers from the LM filtering to the tree positions from TLS is measured at 0.89 m.


ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

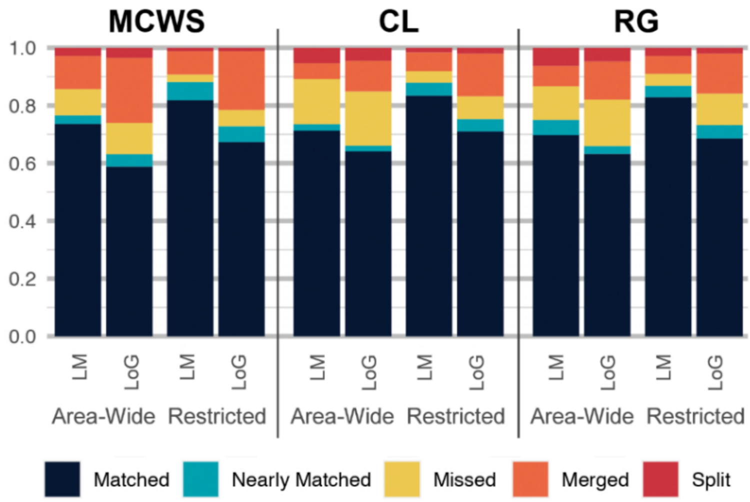


Figure 3: Categories of tree delineationperformance of three crown segmentation methods based on two tree detection results as well as different spatial units (area-wide approach vs. restricted to street green layer).


Figure 4: Visual comparison of markers from LM filtering and tree crowns based on MCWS with TLS tree positions.Aerial imagery is provided by Geobasisdaten© Landeshauptstadt München - Kommunalreferat -GeodatenService 2021.

## 5.2 Quantification and characterization of urban trees in Munich

According to our analyses, there are 1.54 million trees in Munich. This result was achieved based on the two-staged approach of area-wide analysis with subsequent refinement using the approach restricted to the street green layer. For ITCD for the entire city of Munich, LM filtering in combination with MCWS was used due to superior performance based on the accuracy assessment using 952 reference trees from visual interpretation.Figure 5 shows the spatial distribution of the urban forest of Munich in terms of the number of trees per hectare. The result is illustrated based on 100x100m² grid cells. As expected, lowest numbers of trees were found in the city center as well as in areas of high built-up density. In addition, few trees are located over agricultural areas. Highest numbers of trees are displayed in green to blue colors and can be attributed to parks and forests at the outskirts of the city.

On average, urban trees of Munich are 12.45 m high, with a mean crown height of 8.70 m and a mean crown area of 60.31 m². According to the land use data set, street trees (9.1 %), residential trees (38.4 %), park trees (33.1 %), and trees on other land use (19.4 %) were distinguished. The total area covered by tree crowns is 92.84 km², with 6.95 km² (7.49 %) street trees, 28.25 km² (30.4 %) trees in residential areas, 42.24 km² (45.5 %) in parks, and 15.40 km² (16.6 %) crown area of trees on other land use. Overall, park trees exhibit the largest as well as highest crowns with great variability of height levels in the urban forest of Munich. In contrast, trees on residential areas feature relatively small crowns with low height. Street trees are characterized by a clear concentration in the height level between 5 and 10 meters. The detailed statistical distributions of crown area as well as mean crown height are illustrated in Figure 6.

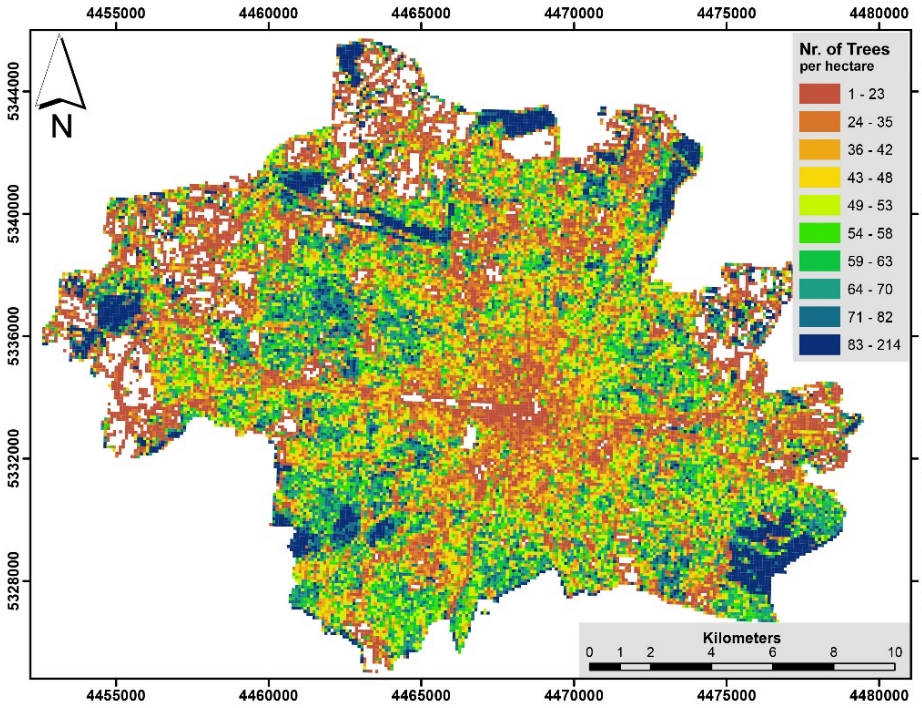


Figure 5: Number of trees per hectare in Munich.

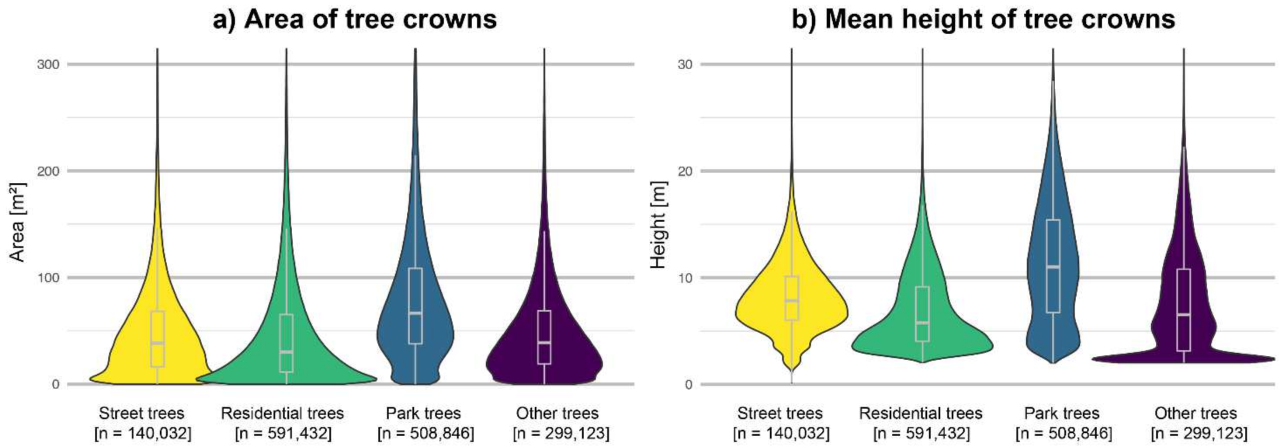


Figure 6: Crown area (a) and mean crown height (b) for urban trees on different land use in Munich.

Figure 7 presents the number as well as crown area of urban trees on different land use depending on the distance fromthe city center. Despite their small absolute number, street trees have ahigh share of up to 50% of all trees in the city center. Towards the outskirts of Munich, the number of park trees increases at the expense of residential as well as street trees. Nevertheless, the canopy area of park trees remains constant suggesting larger trees with increasing distance from the city center.In general, tree crown area is very low in the city center and increases to a constant share of about 25-30 % from a distance of about 3 kilometers. In this area in Munich, the dense inner-city block development transitions to less dense built-up structures.

This transition also becomes apparent in Figure 8a, which shows the dominant land cover of buildingsin the city center and its decreasing area proportions compared to tree crown area with increasing distance to the city center.Towards the outskirts of Munich, buildings account for area shares of only around 10-15 %, whereas trees occupy an areal share of about 25-30 %.The relationship between tree crown area and building density is also depicted in Figure 8b, which reveals tree crown coverage of around 25 % for building density up to 25 %, and decreasing crown coverage with increasing building area. In the class of the highest building densities (i.e. 75-100 %), trees play a negligible role with mean relative crown coverage of 1 %.


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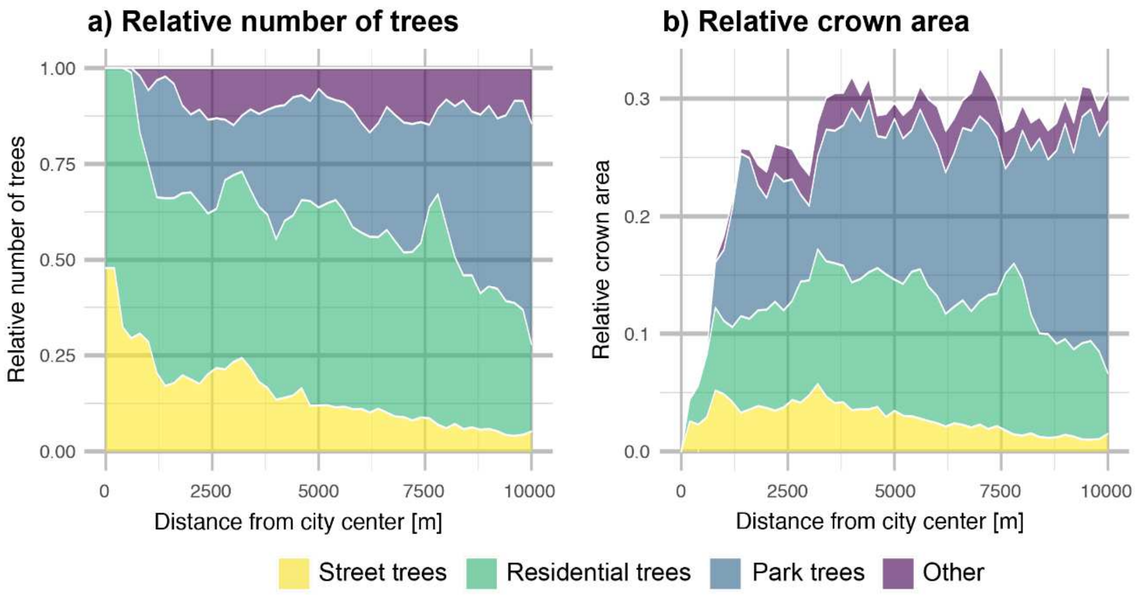


Figure 7: Relative number of trees (a) and relative crown area (b) of urban trees depending on distance from the city center.

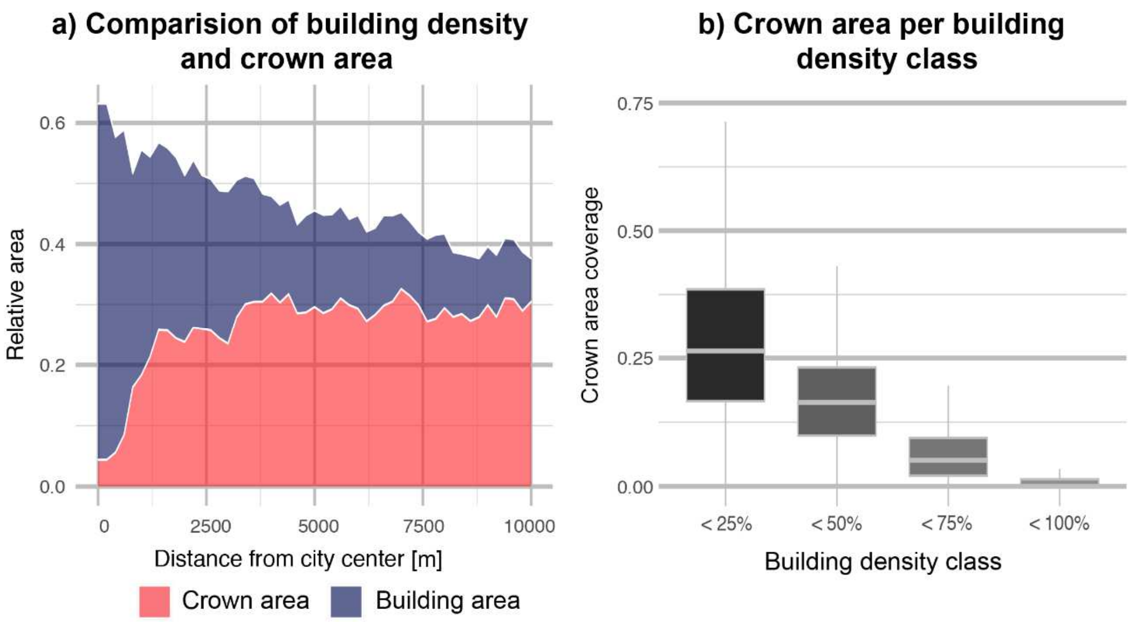


Figure 8: Comparison of building and crown area depending on distance from the city center (a) and statistics of crown area per building density class (b) of urban trees in Munich.

## 6 DISCUSSION

This study evaluates different methods for individual tree detection and crown delineation (ITCD) using remotely sensed and auxillary data in the urban forest of Munich. Compared to literature, this study conducts ITCD in an urban forest, whereas the majority of other studies developed and applied such methods for natural forests (Zhen, Quackenbush, & Zhang, 2016). As data basis, we rely on aerial imagery with very-high spatial resolution (VHR), which is collected regularly for many cities worldwide as well asfor German cities in particular.Considering the broad availability of aerial imagery and the high degree of automation of methods, ITCD can be transferred with little effort to other cities and study areas. In addition, the practical implementation usingthis source of remotely sensed data is facilitated together with the approach requiring only little additional information.

Tree detection based on the CHM from stereo aerial imagery performs well on different land use as well as in various tree densities across the study area of Munich. Regarding the implemented methods for tree detection, LM filtering performs better within rows of trees and detects more trees within groups. LM filtering also favors central points within large trees, whereas LoG blob detection tends to offset the marker.In case of tree crown delineation, the input markers possess larger influence on the result than the segmentation method (i.e., MCWS, CL, or RG) itself with the slightly highest overall accuracy in case of MCWS. However, the proposed two step implementation of tree detection and crown delineation allows to substitute individual processing components and to replace markers by available tree positions, for example from TLS surveying.Validation of the results showed good performance of ITCD compared to reference tree trunk positions as well as reference crown segments from visual stereo image interpretation. However, tree detection based on top view remote sensing captures treetop positions compared to tree trunk positions from the reference data and implies a spatial displacement dependent on vertical tree structure. Nevertheless, validation revealed good agreement with average spatial offset less than 1 m. In addition, the reference data set focuses on street trees as well as small groups of treesnearby infrastructure and biases validation at the expense of trees on other land use to a certain degree.

In this study, we found 1.54 million trees in Munich. To date, there are no reliable comparative statistics. Other unconfirmed estimates of the number of trees in Munich vary widely.Based on the good agreement of reference data as well as the street tree location data of Munich from mobile TLS data compared to the estimates from this study, high reliability and general suitability for practice can be assumed.The value of this approach is also reflected in the factthat municipal data bases target public spaces only and trees on private properties are omitted. The analysis in this study revealed one third of all urban trees on private residential areasin Munich, with limited possibilities for public management(Kronenberg, Łaszkiewicz, & Sziło, 2021) but equally important functions and ecosystem services. In contrast, the potential for tree management is high for street trees (Zölch, Maderspacher, Wamsler, & Pauleit, 2016), which were identified with highest share in the city center with high building density. However, these areas are particularly associated with the greatest challenges and highest vulnerability in the context of sustainable and climate change-adapted urban development.

## 7 CONCLUSION

This workdemonstratesthe good suitability of VHR remote sensing data for individual tree identification in the urban forest. Different methods for ITCD were implemented and evaluated and the most promising algorithms were subsequently applied to the entire city area of Munich. For tree detection, superior results were achieved by LM filtering compared to LoG blob detection with highest values of F-score, precision, and recall of 0.95, 0.99, and 0.94, respectively. Regarding tree crown delineation, the three segmentation methods showed less influence on the resulting tree crowns compared to the input tree positions.For area-wide detection and delineation of the urban forest of Munich, ITCD based on LM filtering as well as MCWS was applied. Refinement based on additional data of street green was conducted in order to add few remaining very small roadside trees. Overall, the two-staged approach showed good performance for the entire city of Munich, with 1.54 million individual trees detected, delineated, quantified, and characterized.

Due to the great importance of the positions of the individual trees (markers), future methodological work is suggested tofocus on this aspect. For example, (Zehner, 2021) proposed an aggregation approach in order to merge results from different procedures for tree detection. Also different sources of data should be considered and integrated for detection of tree positions. In particular side and street view data such as mobile TLS which was used for the street tree location data of Munich offers high potential in this regard. Such data could be utilized as source of tree trunk positions in combination with top view remote sensing data for detailed identification of street trees. Also other sources of VHR remote sensing data (e.g. satellite data with additional spectral channels) offer in-depth capabilities for characterization of the urban forest, like the assessment of tree vitality and detailed treespecies classification.

The results of this study can be utilized in a variety of different contexts. In addition to the management of urban trees and the completion of its municipal responsibilities(e.g., tree maintenance, traffic safety, etc.), municipalities can incorporate information on individualtreesinto urban planning or urban climate analysis. In addition, the city-wide establishment of suitable indicators regarding urban climate, social dimensions, or neighborhood effects becomes feasible. In a broader context, detailed data on urban trees enables area-wide estimation of ecosystem services and contributes to the assessment and acomplishment of sustainable urban development.

## 8 ACKNOWLEDGEMENTS

This research was conducted in the context of the AgB (Alles im grünen Bereich) project funded by the German Federal Ministry of Education and Research, BMBF. Funding codes033LK004Aand 033LK004B. This study was partly funded by HGF-initiative: "HI-CAM: Helmholtz-Initiative Climate Adaptation and Mitigation: two Sides of the same Coin". The authors would like to thank the administration of the city of Munich (Dr. Maria Dobner, Hans Asche) for providing VHR aerial imagery as well as reference data.

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ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER