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Improving methods to calculate the loss of ecosystem services provided by urban trees using LiDAR and aerial orthophotos

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ABSTRACT

In this paper we propose a methodology for combining remotely sensed data with field measurements to assess selected tree parameters (diameter at breast height (DBH) and tree species) required by the i-Tree Eco model to estimate ecosystem services (ES) provided by urban trees. We determined values of ES provided by trees in 2017 in Racibórz (a city in South Poland) and estimated the loss of ES from January 1, 2017 to March 5, 2017, a period of changing legislation that temporarily allowed removal of trees on private property without any permission from city authorities. We applied Canopy Height Models (CHM; GSD 1.0 m) generated from two sets of ALS LiDAR point clouds (acquisitions on June 11, 2011 and March 5, 2017) and performed tree crown segmentations using the GEOBIA approach. Physical attributes were estimated for each tree using predictive models, developed based on field tree inventory . The reference areas for parameterizing the segmentation algorithm and assessing tree species composition were established in Racibórz, while reference data required for assessment of DBH were obtained from the MONIT-AIR project (from Municipality of Kraków). We found that in 2017, 988.79 ha of Racibórz (13.2 % of city area) was covered by the crowns of 264 471 trees, providing ES structural values worth over 384 mil €. The structural value of ES lost in the first months of 2017 (during which 5 075 trees were removed) was about 3.5 mil €. We concluded that in the face of information on tree crown cover that is often missing from city databases, tree inventories require application of a combination of multi-source and multi-resolution spatial analyses, including: administrative decisions for tree removal with exact location, predictive modelling of selected biometrical tree information, automatic crown segmentation on CHM and interpretation of regularly updated color infrared (CIR) aerial orthophotos.

1. Introduction

Green infrastructure is an increasingly valued and necessary element for the sustainable functioning of cities, in the face of economic and social changes and increasing urbanization that often leads to the creation of megacities. The occurrence of trees (high vegetation) in cities, which form a main part of urban forests (UF), is key to promoting the well-being of city residents and are an important element of smart city infrastructure (Johnston, 1996; Konijnendijk et al., 2006). Trees provide a number of important ecosystem services (ES), defined as direct benefits that nature provides to city residents (Costanza et al., 1997; Nowak et al., 2000a; MEA, 2005; Fisher et al., 2009). These include all main types of services: provisioning (e.g., wood, nuts and fruits), regulating (e.g., reducing the extent of the urban heat island effect), supporting (e.g., hydrological regulation, wildlife habitat) and cultural (e.g., aesthetics) (Nowak and Dwyer, 2007; Takács et al., 2016; Dorst et al., 2019). Although ES can be identified and quantified, and although there are social costs to maintain trees, ES are often taken for granted and their economic value is often not recognized (Kabisch et al., 2016).

Up to now, tree valuation models have mainly been used to assist local authorities in achieving an appropriate compensation level where publicly owned trees were damaged or removed without consent. A

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well-known tool for calculating values of ES provided by urban trees is the i-Tree Eco model (USDA Forest Service). This model quantifies environmental functions, including air quality improvement, storm water control, carbon sequestration, and carbon storage by trees, as well as annual and total benefits, using standard ES approaches. Mathematical models running in i-Tree Eco application use data on air pollution and local meteorology, along with vegetation inventory data. The minimum tree attributes required for i-Tree Eco are tree species and diameter at breast height (DBH). The model quantifies vegetation structure and the associated annual value of ES in specific locations (Nowak and Crane, 2000b). For example, in New York City, i-Tree Eco was applied to calculate the value of ES of city trees, revealing that they provided $5.60 in benefits for every $1.00 invested in tree planting and care (Nowak et al., 2007). To carry out comprehensive analyses of ES in cities, an updated and detailed greenery inventory is needed. Usually, only public urban forests or parts of them, such as parks or street trees, are inventoried using a Geographic Information System (GIS) (Klobucar et al., 2020). An approach that has often been used is the GreenSpaces (formerly R3 TREES) application (R3 GIS), which has been employed by 129 cities in Europe (www.r3-trees.com) to support the management of green areas. Urban forest databases are often incomplete or infrequently updated because traditional ground-based surveys are costly and labor-intensive (Zürcher, 2017). Notably, due to the lack of urban forest inventory performed on private land, crucial information about trees in these areas is missing (Konijnendijk et al., 2006).

Until now, research on ES provided by urban trees has for the most part been carried out using a sub-section of a city or for a single, specific ES using data from traditional tree inventories, interviews, surveys or visual interpretation of aerial orthophotos (Camps-Calvet et al., 2016; Dennis et al., 2016; Mariani et al., 2016). However, these methods have difficulty providing comprehensive coverage of relatively large areas, including both private and public properties at the city-wide level (Zhang and Qiu, 2012; Randrup and Jansson, 2020). Therefore, there is a need to develop cost-effective solutions for urban planners to monitor trees and estimate ES so that effective management can be carried out with reasonable effort. The increasing availability of different sources of remotely sensed data, e.g., satellite, hyperspectral, aerial photographs and LiDAR (Light Detection and Ranging) point clouds, offers a fast and replicable way to quantify urban forest dynamics that allows monitoring of private properties and hard-to-reach areas (Alonzo, 2015; Lafortezza and Giannico, 2019). The spatial (horizontal and vertical) structure of vegetation can be analyzed using Airborne (ALS) or Mobile (MLS) Laser Scanning 3-D point clouds, which offers penetration through the canopy to obtain precise information about tree biometric attributes, such as height, crown diameter, position (XYZ), volume of trunk or crown and leaf area (Holopainen et al., 2013; Wężyk et al., 2016). However, in places with a mosaic of multiple tree and shrubs species and age groups, the automation of measurements is complicated due to the higher degree of spatial heterogeneity (Zhang et al., 2015; Sanesi et al., 2019). The most common method for quantifying urban forest structure and ES in these cases is to supplement remotely sensed data with ground sampling. However, taking intensive structural measurements on private property throughout a city is difficult, and averages results obtained from sample inventories are not spatially explicit.

Bagstad et al. (2013) indicated that in order to become common practice, ES assessments should be "quantifiable, replicable, credible, flexible, and affordable". The practical use of ES assessments requires that methods be cost effective and time efficient (Villa et al., 2014). Alonzo (2015) used fused airborne hyperspectral and LiDAR data to carry out an analysis of an urban forest ecosystem in i-Tree Eco, and demonstrated that it is reasonable to use LiDAR to measure LAI in an urban environment lacking a continuous canopy and characterized by high tree species diversity. Giannico et al. (2016) assessed forest stand volume and above-ground biomass in the urban forest using a combination of LiDAR-derived metrics, which can be used to estimate selected ES, but they did not identify measurable benefits of urban trees. Although ES provided by trees in cities have been actively studied, LiDAR technology (ALS or MLS) is not at present widely used for urban tree inventory (tree cadaster). In urban research in New York, the most relevant ES that played a role in decision-making were rainwater infiltration (reduced water runoff), carbon storage, air pollution removal, local climate amelioration, and recreation (Kremer et al., 2016). However, many landlords and most residents are not aware of the economic value of UFs and are even less aware of the loss of value caused when trees are removed. For remotely sensed urban forest inventory to be operationalized (Alonzo, 2015), and as numerous cities have gained access to high-accuracy digital terrain model (DTM), digital surface model (DSM) and LiDAR data, it is a reasonable next step to implement simpletree segmentation algorithms to generate serviceable crown objects for further analysis.

Currently, information concerning the value of ES in cities is missing. In order to address the absence of such data, robust methods integrating multi-source, publicly accessible data for monitoring ES provided by urban trees, as well as its changes, e.g., as a result of urban tree removal, are highly important to improve environmental awareness of the importance of the urban forest. In some cities, removing trees from private property is regulated by laws that specify the conditions necessary to obtain a permit for tree removal. However, many cities still do not have regulations regarding the protection and felling of urban trees (Lavy and Hagelman, 2019). In Poland, removing trees or shrubs from private property may only take place by permit for trees of a specified diameter (at a height of 5 cm above the ground) (Act on Protection of Nature, 2004). Penalties for illegally removing a tree depend on its species and the circumference of the tree trunk at a height of 130 cm (Regulation of the Poland's Minister of the Environment, 2017) and range for 1 cm trees from 3 € (e.g., *Acer negundo*) to 50 € (e.g. *Taxus baccata*). However, on January 1, 2017, the requirement for a permit for tree removal in Poland was suspended temporarily. The rationale for suspending the need for a tree removal permit was that it was causing an increasing administrative burden, even though the vast majority of applications ended in permits being issued. In any case, the change of law was controversial and in some cases led to unregulated cutting of large trees. After half a year, on June 17, 2017, the mandatory permit requirement was restored. Nevertheless, despite fierce media discussion about the destructive impact caused by the suspension of permits, the number of trees felled and the impact on ES have not yet been investigated.

In our study, we present an approach to improve the measurement of urban trees and the calculation of ES dynamics that can provide a feasible approach for city administrators having access to ALS point clouds, and which can be aligned with cadastre databases of urban trees. Our method uses automated data processes to establish a relationship between the measurement of tree characteristics in situ and ALS LiDAR data. The approach estimates urban tree characteristics based on predictive models, generated using point clouds and tree inventory from ground reference plots, which can provide an alternative to large area field measurement campaigns and also improve the cost-benefit ratios in assessing ES. The main goal of our research was to estimate ES provided by trees based on predicted and standardized characteristics of trees from the city of Racibórz (Poland) using the i-Tree Eco model. We show how gaps in tree inventory data can be estimated and added to the i-Tree Eco model to perform a fast and accurate estimation of ES values provided by urban trees. We applied the method to estimate the loss of ES caused by tree removal during the temporary suspension of mandatory permits for tree removal on private property in Racibórz.

2. Materials

2.1. Study area

The city of Racibórz, Poland was selected as our study area (Fig. 1). This municipality is a typical urban area, with complex spatial

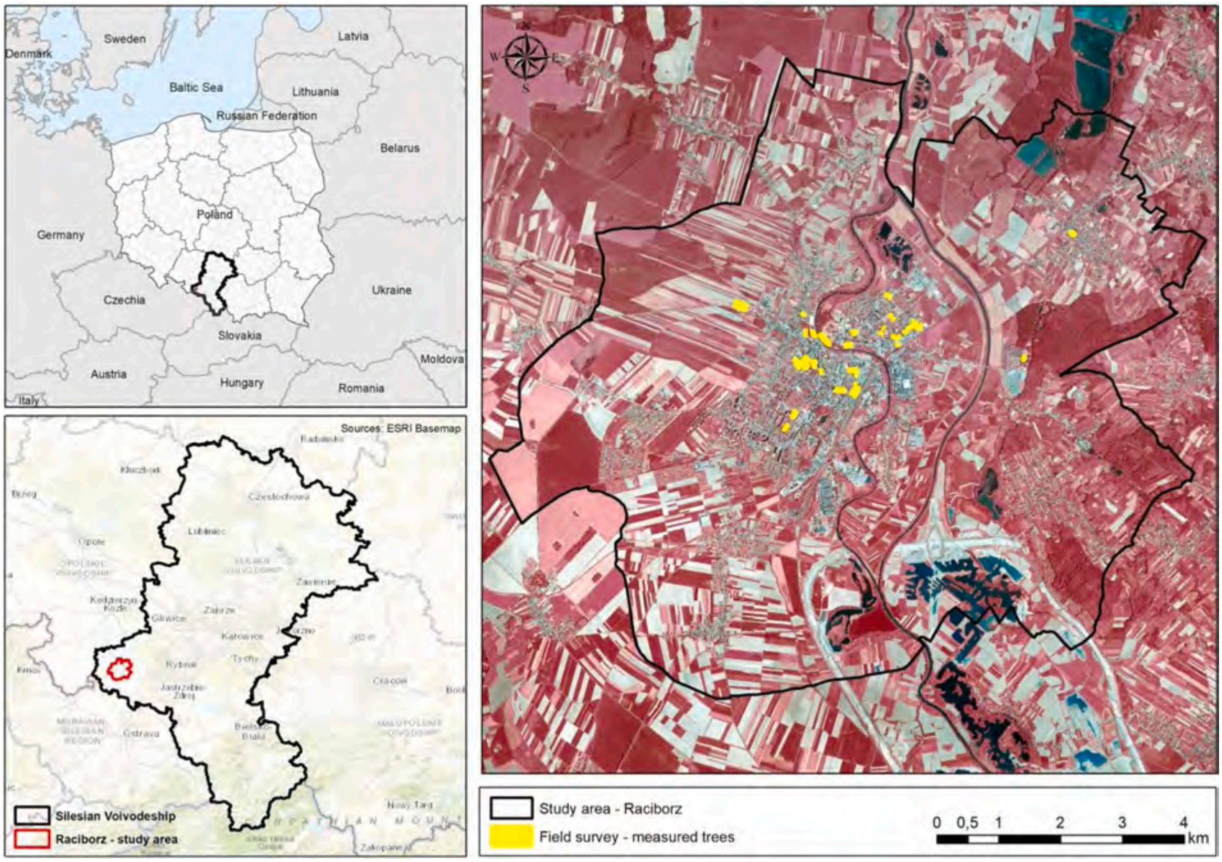

Fig. 1. The study area in Racibórz. Field survey areas (polygons of tree inventory) are shown in yellow on the CIR orthophotomap (2015) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

assemblages of vegetation, creeks, buildings, roads, and other man-made features. The total area of the city of Racibórz is 75 km^2. In terms of the structure of land use and land cover, agricultural lands cover 68.9 %, forests 3.7 %, and built-up areas cover 22.9 % of Racibórz. Protected areas account for approximately 17 % of the city. As of 2019, the town had a population of approximately 50 000 inhabitants (STAT, 2019).

2.2. Datasets

In this study, we used archival ALS LiDAR 3D point clouds (from June 2011 and March 2017; density 12 pts/m^2), and CIR (color-infrared) aerial orthophotomaps (2015; GSD 25 cm) available from the Head Office of Geodesy and Cartography (GUGiK) in Poland. Point cloud classification was conducted by the surveying companies contracted by the GUGiK according to the ASPRS standards, i.e., class 2 - ground, 3 - low vegetation (0.0−0.4 m above ground - AGL), 4 - medium vegetation (0.4–2.0 m AGL), 5 - high vegetation (2.0-max Z), 6 - buildings (with H > 2.0 m that meets specific surface area and roof planarity parameters). The database of trees felled in 2017 was supplemented with aerial orthophotomaps in natural colors (RGB) from September 2016, available as a base map in Google Earth (Table 1).

Table 1
Details of geospatial data used in this study.

Data type	Data acquisition date	Resolution
ALS LiDAR point cloud	June 11, 2011; March 5, 2017	~ 12 pts/m^2
Orthophotomap CIR	June 7, 2015	0.25 m
Orthophotomap RGB (Google Earth)	September 1, 2016	0.15 m

To supplement collected data sets, a field survey in Racibórz was conducted in June 2019 (Fig. 1), where 41 reference plots, with an average size of 0.4 ha, were established. A basic inventory has been made for 1 885 trees, considering the tree species, DBH and determining the number of visible and invisible trees (those growing under the canopy of larger trees) on orthophotomap. Data collected in field plots were used to parameterize and evaluate the accuracy of the algorithm for tree crown segmentation and to determine tree species in the analyzed areas. For the test plots (AOIs), areas were selected where tree removal had not been carried out in recent years (e.g., public parks), so that the number of trees measured in the field corresponded to the number of trees identified on the ALS LiDAR point cloud acquired in March 2017.

Additionally, the tree inventory data obtained in June 2016, shared by the municipality of Kraków's Green Space Authority, collected during the implementation of the project "Integrated monitoring of spatial data for improving air quality in Kraków – MONIT-AIR" (EEA Grants), was used. This dataset included precise measurements of 3 692 trees performed in selected Kraków parks. For each tree, the DBH, height (H) and crown diameter (CD) were measured and the tree species was determined in the database. These reference data were used to develop a predictive model of DBH prediction, since DBH together with tree species is required by i-Tree Eco for calculating ES.

Because i-Tree Eco also requires air pollution and local meteorological information, the newest data (2015) from the measuring station located in Katowice, the nearest to Racibórz (NCEI ID: 125600−99999), was used. A query from the decision database of tree removal in 2017 (with exact locations of trees) was obtained from the offices of Racibórz County in which it is found. The information in the database included, i.e., date of issuing the decision, address, parcel ID, number of trees, and tree species. The data was used to determine the number of trees felled in 2017 for which a permit was granted, compared to the period of changes in the legislation when obtaining a permit was not necessary from January 1, 2017 to February 28, 2017.

3. Methods

The calculation of ES for urban trees in Racibórz required integration of multi-source datasets and different methods of data analysis. The workflow of the analysis is presented in Fig. 2. In the following paragraphs we present a detailed description of all the steps of the analysis.

3.1. Segmentation of single tree crowns – creating Urban Tree Cover layer for Racibórz

Based on the ALS LiDAR point clouds, a Digital Terrain Model (DTM), two variants of normalized Digital Surface Model (nDSM, nDSM_buildings) and Canopy Height Model (CHM) were generated (GSD 1.0 m) using FUSION software (McGaughey, 2015). After creating DTM, the point clouds were normalized by subtracting the DTM elevation from the corresponding ALS points. The nDSM was created based on the following point cloud classes: 2, 3, 4, 5, 6. The nDSM_buildings layer was created using points from class 2 (ground) and 6 (buildings). For generating the CHM the points from classes 2, 3, 4 and 5 (low, medium, and high vegetation) were used. The nDSM, nDSM_buildings, CHM, and CIR aerial orthophotomaps were used to preliminarily classify city areas with tree crown cover. The segmentation and classification were performed using the Geographic Object Based Image Analysis (GEOBIA) approach based on the rule-set prepared in eCognition Developer 9.3 (Trimble Geospatial) software. It was assumed that the crown of a single tree should have an area of at least 3.0 m^2, and the minimum crown height should be at least 3.0 m from the ground. Adopting a minimum tree height of 3.0 m was intended to eliminate areas covered with shrubs, for which it was difficult to perform segmentation accurately. The analyses were performed separately for ALS collected in 2011 and 2017.

Within areas classified as covered by tree crowns, single tree crown segmentation was performed based on CHM from 2017. For this purpose, the inverted watershed segmentation algorithm implemented in eCognition Developer was used (“watershed segmentation”). It is a segmentation algorithm using the local minima of the indicated raster layer, which are treated as so-called “seeds” from which segments expand into adjacent pixels with higher values (Vincent and Soille, 1991). The growth region of segments (tree crowns) occurs until it comes into contact with the next segment’s border growing from adjacent seeds. In this case, the reversed top of the tree, i.e., the lowest point in the reversed model, sinks. The described segmentation algorithm defines the minimum height (3.0 m) and size (3.0 m) of created segments. This algorithm works well in forest conditions, especially in Scots pine (*Pinus sylvestris* L.) stands managed by an even-aged logging system, where adjacent trees have similar size (Wężyk et al., 2016). In the case of urban green areas, small and big trees often grow next to each other, making it difficult to parameterize the segmentation algorithm and correctly separate all trees (Hu et al., 2016). Increasing the minimum crown area means that the crowns of small trees are attached to adjacent crowns. On the other hand, using too small a minimum size for segments can result in the algorithm identifying segments of the same crown (sub-crowns), as crowns of different trees, while they actually belong to the same tree.

In order to minimize the occurrence of these crown delineation errors, the segmentation algorithm was parameterized using data collected on 41 reference plots (averaging 0.4 ha) established in June 2019 in Racibórz. In the first step, segmentation of the crowns was performed on the CHM model (2017) using the same segmentation parameters for all tree crowns. Based on the analysis of errors in the next step, the segmentation was performed in two stages using different parameters for trees lower- and higher than 16.0 m. The "watershed segmentation" algorithm implemented in eCognition software enables to define certain criteria under which two initially distinct seeds (initial tree crows) are merged. The available criteria enable to control over- or under-segmentation of tree crowns. The selected criterion is evaluated

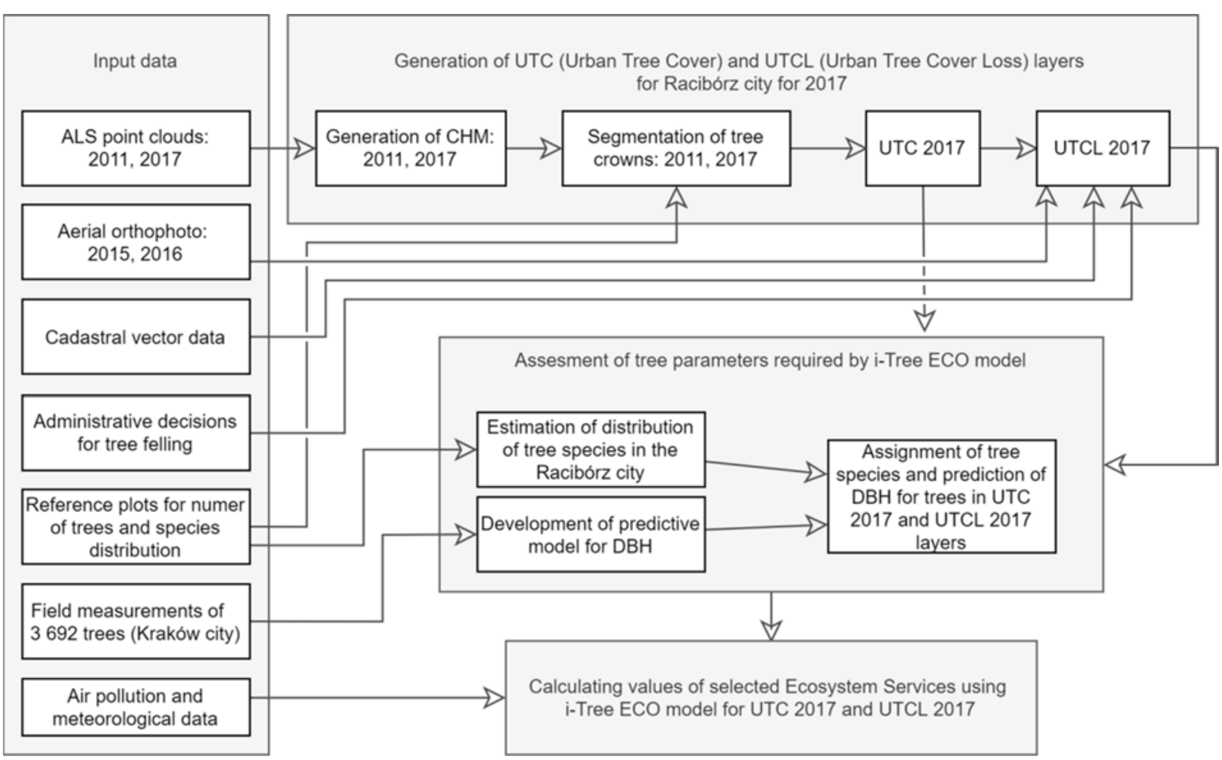

Fig. 2. Workflow of analyses (ALS – airborne laser scanning; CHM – canopy height model; DBH – diameter at breast height; UTC – urban tree cover; UTCL – urban tree cover loss).

when two objects start having a common border during the iterative segmentation process. In this study, we used the "Ovfl. Volume" criteria (parameter) to merge the neighbor seeds. For calculating the "Ovfl. Volume", for each pixel, the difference to the current intensity maximum is evaluated and the sum of these values corresponds to the "volume" (amount of "water" in the "valley"). If this volume is below the defined threshold value, seeds are merged into neighboring initial crowns/seeds. For the first step of tree crown segmentation, applied to the whole area previously classified as covered by tree crowns, the Ovfl. Volume parameter was set to 0.35. Then, the tree crowns with height lower than 16 m (maximum pixel values within the crown segment) were merged together and then segmented again. For these areas with crowns lower than 16 m, the Ovfl. Volume parameter was changed to value 0.25.

The segments representing tree crowns obtained by GEOBIA formed the Urban Tree Cover (UTC) layer for Racibórz in 2017. This layer was exported to vector format (ESRI Shapefile) with information on crown area and tree height.

3.2. Estimate of the number of trees felled during changes in legislation in 2017

Our analysis concerned the period from January 1, 2017 to February 28, 2017, because beginning March 1, felling was limited to those obtaining a special permit issued by the Regional Directorate for Environmental Protection, to protect birds during their breeding period (as stated in the so-called Birds Directive). The number of trees felled from January 1 to February 28, 2017, was estimated using remote sensing data (Table 1).

In the first stage of the analyses, areas covered by vegetation in 2011 were classified. For this purpose, pixels identified by CHM (in 2011) with a height of at least 1.0 m above ground were distinguished. Then, the Normalized Differential Vegetation Index (NDVI) was calculated on the basis of the CIR aerial orthophotomap from 2015; areas with NDVI values <0.05 were eliminated from further analysis. The application of NDVI allowed the elimination of areas where tree crowns were absent in 2015. For areas with NDVI values greater than or equal to 0.05, crown segmentation was performed on the basis of CHM from ALS data (2011), using an inverse watershed algorithm. Then, segments for visual verification were identified for which CHM pixels from 2017 of less than 0.5 m occupied at least 40 % of a given segment's area (i.e., identification of 40 % loss of crown area). This operation was used to initially limit the number of trees requiring visual verification. These crowns were then visually verified, during which the operator analyzed each segment on a screen and decided whether a tree could have been removed in the analyzed period of January–February 2017. If a verified segment was located in a place where a tree did not exist on the orthophotomap from 2016, the segment was removed. For the verification process, very high-resolution RGB aerial orthophotomaps (from Sep. 1, 2016) available through Google Earth were used.

In order to estimate the number of trees removed during the period administrative permits were not required for private landowners (Jan. 1–Feb. 28, 2017), the databases were contrasted with information on tree removal permits issued by the local administrative office. Trees for which felling permits were issued in the period Sep. 1, 2016–March 5, 2017, were removed from the database. This analysis provided an Urban Tree Cover Loss (UTCL 2017) map and dataset for Racibórz.

3.3. Estimating diameter at breast height and making species assignments

Tree species (or genus) was assigned and DBH estimated for each tree in the UTC 2017 and UTCL 2017 layers, which provided essential information for calculating ecosystem services using i-Tree Eco. Inventory data from the Municipality Greenspace Authority of Kraków (totaling 3 692 trees) was used to develop a statistical prediction model, where tree height and crown area were applied as predictive variables of DBH. We used the Generalized Additive Models (GAM) method to create the prediction model (Hastie and Tibshirani, 1986; Hastie, 2015). Trees were randomly designated to a species using proportions determined on the basis of the inventory results on 41 reference plots established in Racibórz. Only tree species which accounted for $\geq$ 10 % of the trees in the reference plots were taken into account.

3.4. Calculation of ecosystem services provided by trees

The assessment of the structure and value of ES provided by the UF in 2017 and the losses in ES in Racibórz (from Jan. 1, 2017 to Feb. 28, 2017) was conducted using i-Tree Eco. The structural value is the value of a tree based on the physical resource itself (e.g., the cost of replacing a tree with a similar tree) according to the Council of Tree and Landscape Appraisers' valuation procedures, which uses tree species, diameter, condition, and location information (Nowak et al., 2002). The model implemented in the software estimates: 1) forest structural attributes, i.e., the number of trees, species composition, tree density, leaf area and biomass; 2) hourly volatile organic compound emissions; 3) carbon storage and annual carbon sequestration by trees; 4) hourly air pollution removal by trees (ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter <10 microns diameter).

In our study, i-Tree Eco was used to quantify the following main ES: pollution removal (€/yr); carbon storage (€) and carbon sequestration (€/yr); oxygen production; avoided runoff (€/yr) and overall structural value (€). Pollution removal was calculated for O_3, SO_2, NO_2 and particulate matter ($PM_{2.5}$). For this analysis, pollution removal values were calculated based on prices of 32 255 € per Mg of O_3; 4 818 € per Mg of NO_2, 1 755 € per Mg of SO_2, and 1 119 615 € per Mg of $PM_{2.5}$. Estimates of the value of pollution removal are based on either the European median externality values or BenMAP regression equations (Nowak et al., 2014) that incorporate user-defined human population estimates. To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree biometrical data (iTreeEco, 2020). Financial values of carbon storage and carbon sequestration are based on an estimated carbon value of 153 € per Mg (U.S. Environmental Protection Agency, 2015).

According to i-Tree Eco methodology, the amount of oxygen produced is estimated from carbon sequestration based on atomic weights. To estimate the net carbon sequestration rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of the urban forest account for decomposition (Nowak et al., 2007). Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches, and bark may all intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis (iTreeEco, 2020). The value for avoided runoff was calculated based on the price of 1.75 € per m^3.

4. Results

4.1. Crown area and number of trees identified on the basis of ALS point clouds

A spatial database of urban tree cover in 2017 (Table 2) and a map (Fig. 3) containing information on the distribution of trees in 2017 in Racibórz were developed. For each tree, the XY – coordinates (PL- 1992; EPSG: 2180), tree height (m), crown projection area (m^2) and DBH (cm) were estimated and tree species assigned. A similar database describing urban tree cover loss in 2017 with information on trees removed during the period of suspension of mandatory permits was also created, along with a map of removed trees (Fig. 4).

The study showed that on March 5, 2017, approximately 989 ha of Racibórz were covered by the crowns of 264 471 trees (13.2 % of

Table 2
Spatial databases describing urban trees in Racibórz.

Name	Database description	Crown area [ha]	Number of trees
Urban Tree Cover 2017	Date: March 5, 2017 Tree attributes: XY-coordinates PL-1992 CS, height (m), crown area (m^2), DBH (cm), species name (Latin)	988.79	264 471
Urban Tree Cover Loss 2017	Period: January 1, 2017 to March 5, 2017 Tree attributes: XY-coordinates PL-1992 CS, height (m), crown area (m^2), DBH (cm), species name (Latin)	13.05	5 075

Racibórz's territory). During the two months when mandatory tree removal permits were suspended we calculated that approximately 5 075 trees (covering 13.05 ha of the total projected crown area) were felled in Racibórz, constituting about 2% all trees in the city (Fig. 4).

The two-stage crown segmentation procedure resulted in a relatively high correlation between the number of trees identified as a segment (GEOBIA) and the number of trees counted in reference plots ($R^2 = 0.86$; Mean Absolute Percentage Error = 21.1 %; Fig. 5). Moreover, the methodology also resulted in a small (0.3 %) mean percentage error of estimates of the number of trees (Fig. 6).

The predictive model for DBH developed based on field data from Kraków had an R^2 of 0.67. The relationship between DBH and the explanatory variables (tree height and tree crown area) is presented in Fig. 7. The mean absolute percentage error (MAPE) was 6.2 %, and the mean percentage error was 0.0 %. The graph of observed versus predicted values indicates the adjustment made by the model (Fig. 8). Since all trees identified in the segmentation step had information on tree height and crown size, it was possible to estimate DBH using the developed statistical model for all trees in the UTC 2017 and UTCL 2017 layers.

The proportions of trees by genus from the field inventory of 41 reference plots in Racibórz showed that of the 3 most common genera, 44 % were *Acer*, 34 % *Tilia* and 22 % *Fraxinus*.

4.2. Ecosystem services provided by trees in Racibórz in 2017

An assessment of vegetation structure and the value of ES in the UF of Racibórz was conducted based on DBH and tree species, which were estimated for each tree in 2017 (264 471 trees) and analyzed using i-Tree Eco. Two important parameters for determining most ES are leaf biomass and the amount of healthy leaf surface area of a tree. In 2017, tree crowns in Racibórz covered approximately 989 ha, provided 48 km^2 of leaf area with leaf biomass of 2 934 Mg (Table 3).

Pollution removal by trees in Racibórz was estimated using UTC 2017 and recent data on pollution and meteorology. Pollution removal was most significant for ozone (O_3). We estimated that trees in Racibórz removed a total of 51 Mg of air pollutants per year (ozone (O_3), nitrogen dioxide (NO_2), $PM_{2.5}$, and sulfur dioxide (SO_2)), with an associated value for the removal of these pollutants of 4.4 million €. The gross yearly carbon sequestration by trees in Racibórz was 1 948 Mg, with a value of 300 000 €. Trees in Racibórz store 50 775 Mg of carbon (valued at 7 mil €), with *Acer* storing and annually sequestering the most carbon (approximately 53.4 % of the total stored tree carbon and 52.7 % of annually sequestered carbon). Annual oxygen production by the urban forest is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass. We estimate that trees in Racibórz produce 5 210 Mg of oxygen per year. Urban trees and shrubs are beneficial in reducing surface runoff by intercepting precipitation, while their root systems promote water infiltration and moisture

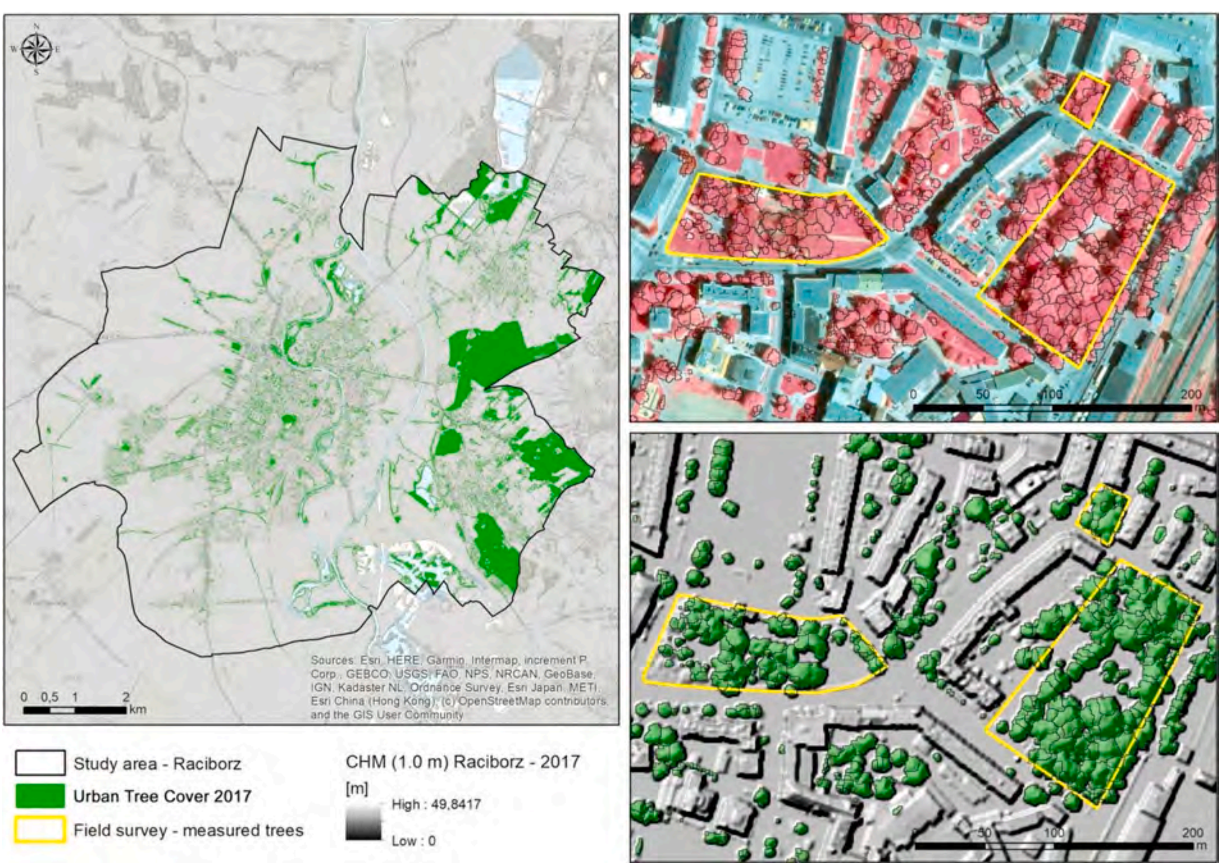

Fig. 3. Left: Results of tree crown segmentation in Racibórz based on CHM from ALS LiDAR (2017); right top: segmentation of tree crowns presented on CIR aerial orthophotomap; right bottom: classification of tree crowns on CHM.

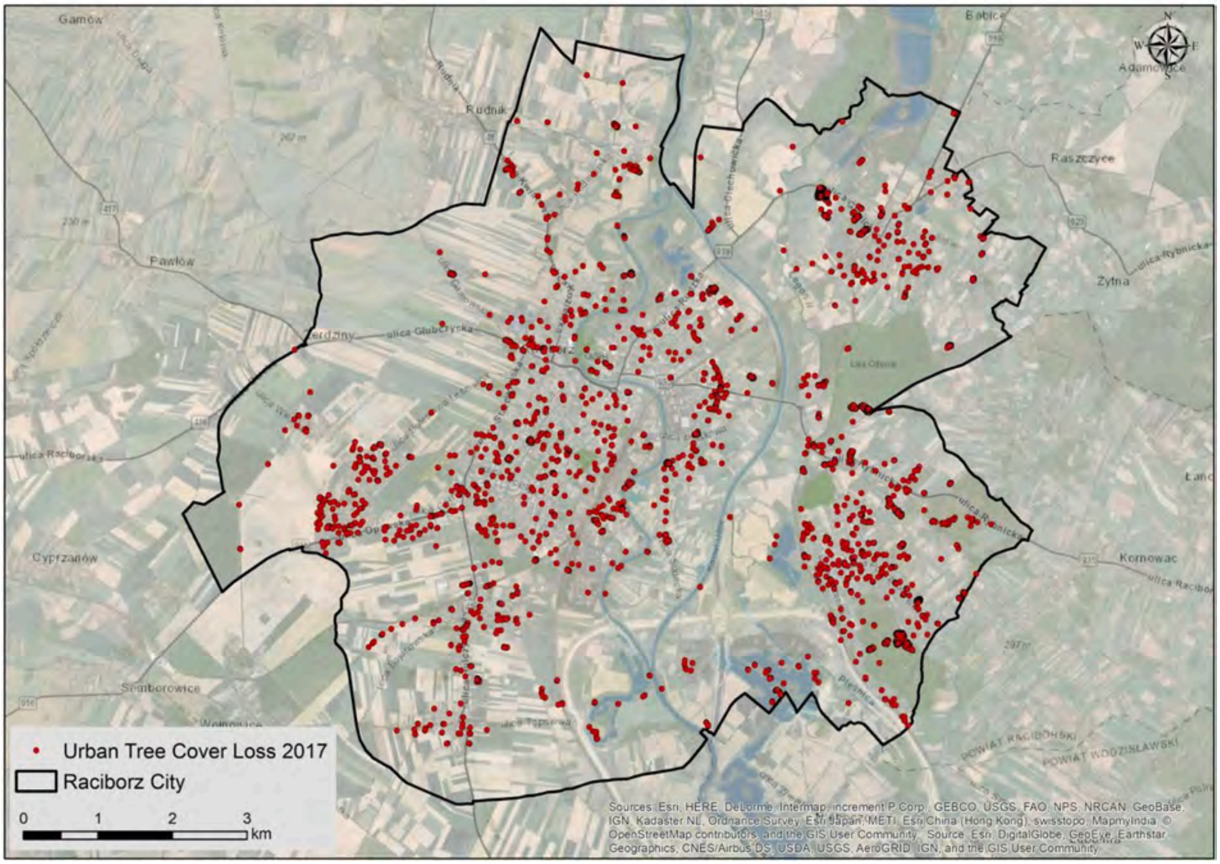

Fig. 4. Trees removed in Racibórz during the suspension of mandatory permits for tree felling (Jan. 1, 2017–Mar. 5, 2017; Urban Tree Cover Loss 2017).

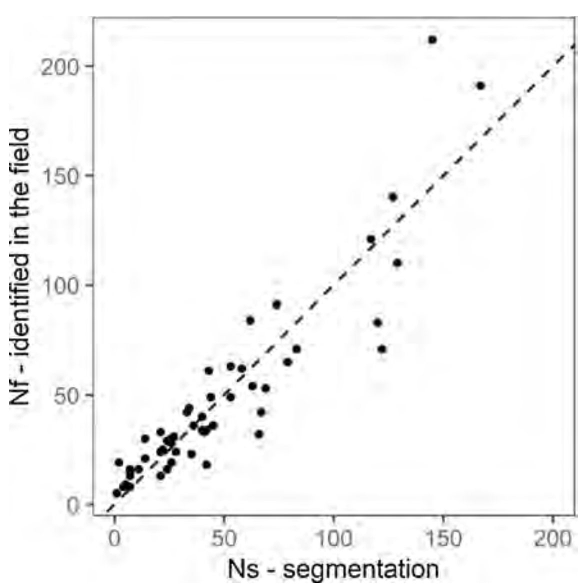

Fig. 5. Comparison of the actual number of trees (Nf) identified on the reference plots with the number of trees derived from segmentation (Ns).

storage in the soil. Trees in Racibórz reduced runoff by an estimated 75 738 m^3 a year estimated based on local meteorological data, which provides an economic value of 130 000 € (Table 4).

The structural benefits provided by urban trees in Racibórz (UTC 2017) were valued at 384.5 mil € in 2017. On average, one tree provided ES worth about 1 454 € annually. The functional benefits of carbon sequestration, avoided runoff, and pollution removal provide a total

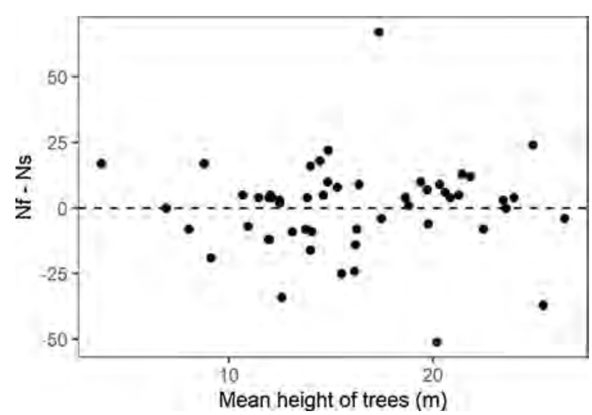

Fig. 6. Differences between the number of trees identified in the field (Nf) during inventory and the number of trees derived from crown segmentation (Ns) in relation to mean tree height.

value 4.8 mil €/yr, which is 640 € of functional benefits per ha per year after standardization. Detailed information about structural values provided by individual trees in Racibórz is presented in Fig. 9.

4.3. Decrease of ecosystem services provided by trees during the suspension of mandatory tree removal permits in Racibórz

Losses in ES were calculated for the 5 075 trees (with a crown area covering 13.05 ha) removed in Racibórz (UTCL 2017) during the suspension of mandatory tree removal permits (Jan. 1, 2017 to Mar. 5, 2017). The decrease in pollution removal caused by tree felling in Racibórz was estimated using a database describing fellings based on

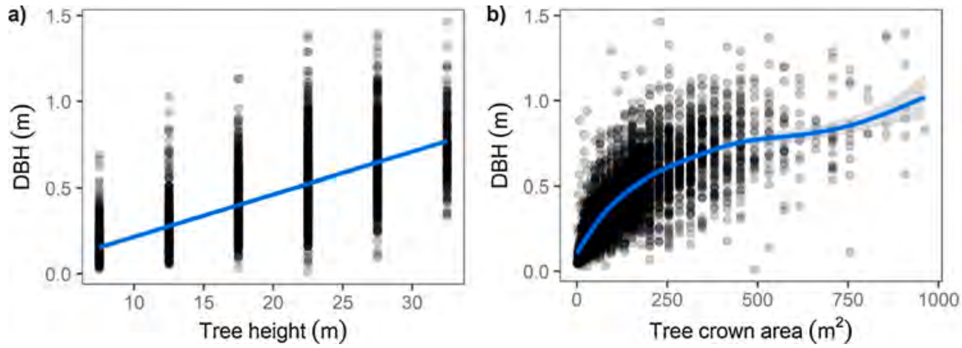

Fig. 7. Dependence of DBH (diameter at breast height) on tree height (a) and tree crown area (b) for trees measured in Kraków within the MONIT-AIR (EEA Grants) project.

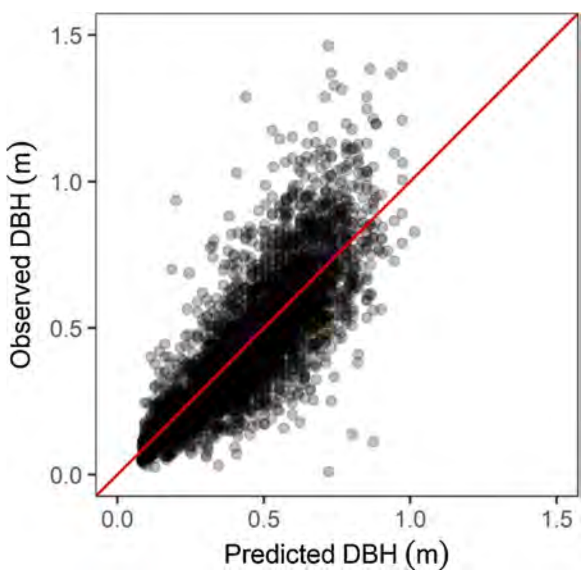

Fig. 8. Observed vs. predicted values of DBH (diameter at breast height) for trees measured in Kraków within the MONIT-AIR project.

Table 3
Characteristics of the three most common tree genus in Racibórz.

Genus	Percentage *[%]*	Number of trees	Total leaf area *[km²]*	Leaf biomass *[Mg]*	Tree dry weight biomass *[Mg]*
Acer sp.	44.0	116 367	24	1 362	54 282
Tilia sp.	34.0	89 920	15	699	24 944
Fraxinus sp.	22.0	58 184	9	873	22 324
Total	**100.0**	**264 471**	**48**	**2 934**	**101 550**

DBH and tree species along with pollution levels and meteorological conditions in 2015. Reduced pollution removal was most significant for ozone. It is estimated that trees that were cut down could have removed annually 600 kg of air pollution (ozone (O_3), nitrogen dioxide (NO_2), particulate matter less than 2.5 microns ($PM_{2.5}$), and sulfur dioxide (SO_2)), providing a value of 46 000 €. There was a loss of gross carbon sequestration by trees that were removed of 19 Mg of carbon per year, with an associated value 3 000 €. The removed trees were estimated to have stored 393 Mg of carbon (valued at 60 000 €) and were able to produce 53 Mg of oxygen annually. Removed trees could also have reduced runoff by an estimated 776 m^3 a year, valued at 1 300 €.

Trees that were cut down in Racibórz had a structural value totaling 3.5 mil € (Fig. 10) and there was a loss in annual functional value of 50 000 €/yr. The estimated loss of ES from felling one tree "cost the public" an average of 690 € and decreased the value of ES by approximately 1% of the total structural value provided by all trees in Racibórz in 2017. At the city level, this constitutes a loss in the millions €. Total losses of ES in Racibórz caused by tree removal are presented in Table 5.

5. Discussion

Management of urban trees has become increasingly important in recent years, which is shown by the work of urban planners and green space managers in protecting and improving city green infrastructure (EC, 2013). Estimating ES provided by urban trees is useful information for policy- and decision-makers. Tools, such as i-Tree Eco (USDA) and GreenSpaces (R3 GIS), based on updated UF inventory, provide important analytical approaches for urban forest managers and city inhabitants. However, updated and precise geodata necessary for informed and sustainable urban forest management and the determination of the benefits and spatial distribution of ES in cities is often lacking for many metropolitan areas.

The traditional workflow of a city green inventory usually includes collecting information about tree and shrub species, diameter, height and street name or cadastral parcel number. Usually, such inventories are limited to accessible public areas (e.g., parks and squares), which underestimates urban green infrastructure (Östberg et al., 2018). Notably, private land often constitutes the majority of a city's green space, while city parks and gardens include only a fraction of urban green infrastructure. Traditional field methods of urban tree inventory are also highly time consuming and costly (Nielsen et al., 2014). Thus, there is a need for more effective methods of inventorying and monitoring city greenery, including the use of remote sensing (Lee et al.,

Table 4
Ecosystem services and their financial values provided by trees in Racibórz in 2017.

Genus	Carbon storage		Gross carbon sequestration		Pollution removal		Oxygen production	Avoided runoff	
	[Mg]	*[€]*	*[Mg/yr]*	*[€/yr]*	*[Mg/yr]*	*[€/yr]*	*[Mg]*	*[m³/yr]*	(€/yr)
Acer sp.	27 141	4 152 414	1 028	157 254	26	2 191 388	2 746	37 974	66 582
Tilia sp.	12 472	1 908 139	498	76 233	16	1 361 545	1 333	23 589	41 360
Fraxinus sp.	11 162	1 707 702	422	64 635	9	818 049	1 131	14 175	24 854
Total	**50 775**	**7 768 255**	**1 948**	**298 122**	**51**	**4 370 982**	**5 210**	**75 738**	**132 796**

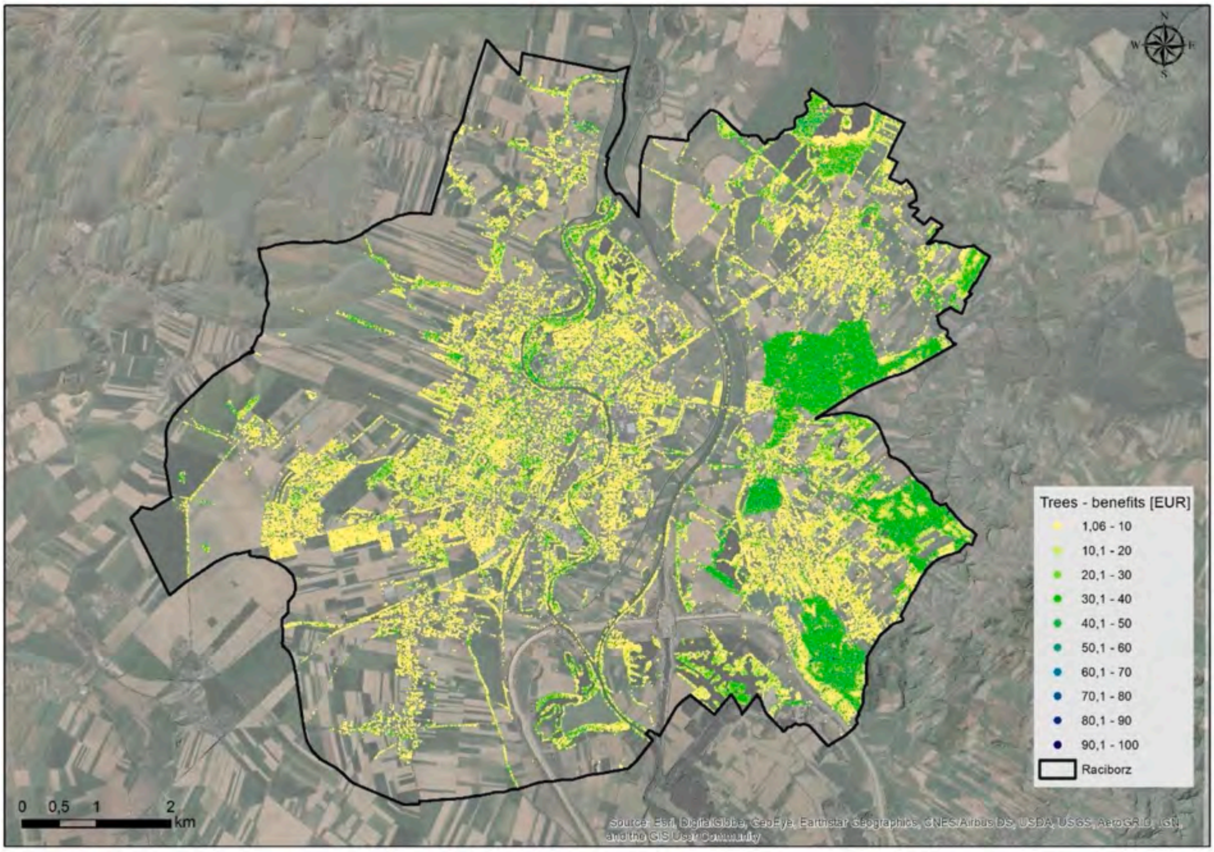

Fig. 9. Total annual value of ecosystem services provided by individual trees in Racibórz in 2017.

2016). To date, successful use of remote sensing for inventorying urban greenery has been based on satellite imagery and ALS point clouds show significant potential (Zhang et al., 2015). However, few studies have been carried out using this approach, especially dealing with integrating ALS point clouds and other remotely sensed data with field measurements and administrative data collected by municipalities.

This study attempts to estimate biophysical parameters for individual trees in an urban area using semi-automatic crown segmentation and predictive models based on field measurements of trees and ALS point clouds. Databases with administrative decisions on tree removal with precise locations and interpretation of CIR aerial orthophotos were used to estimate ES losses due to tree removal. Partial tree inventory of reference plots was necessary for accurate parameterization of the crown segmentation algorithm and tree species composition. For each tree, features such as location, tree height, crown projection area and diameter at breast height were estimated, and tree species assigned. The impact of imperfect crown segmentation on classification accuracy appeared minimal. However, mapping tree species is challenging in urban environments due to the typically fine scale of spatial variation (Welch, 1982) and potentially very high species diversity. Single, well-isolated tree crowns and street trees were more straightforward to delineate using ALS point clouds than heavily overlapping trees on private property or in parks.

The methodology presented here, which employs ALS point clouds and predictive models, allows urban forest inventory gaps to be filled in for an entire city. City-level data generated in this way can be used in i-Tree Eco to estimate ES at a finer scale than was previously possible. The combination of LiDAR point clouds, time series of aerial orthophotos and administrative decisions made it possible to estimate the loss of ecosystem and economic services that occurred due to temporary relaxation of tree removal regulations. Using this approach, it was also possible to identify regions within a city with an insufficient share of green infrastructure or where significant tree losses occurred over certain periods.

Management of urban green areas not only requires periodic and precise inventories, but also increasing community awareness about the benefits of trees. Inventories are instrumental for this task. In this study we use ALS LiDAR data to assess ES losses caused by tree felling. In the case study of Racibórz, the structural financial value of trees cut down in the first months of 2017 (e.g., the cost of replacing a cut tree with a similar tree) amounted to 3.5 mil €. This was seven times greater than the city's annual 500 000 € budget to maintain green areas (BIP, 2018). Total urban forest benefits in Racibórz in 2017 amounted to 384.5 mil €. Our estimate shows that trees provide annually about 7 000 € in services to each resident of Racibórz. The method applied in this study allowed that ES loss to be estimated by detecting trees that were removed, providing a useful proxy for quantifying the effects of city green area policies.

Despite the use of state-of-the-art technology, our study has some limitations. First, the total annual ES benefits of urban trees in Racibórz were underestimated due to the limited number of ES that are evaluated in i-Tree Eco software (i.e., carbon storage, gross carbon sequestration, pollution removal, oxygen production and avoided runoff). Secondly, difficulties in obtaining reference tree inventories on private property in Racibórz could have resulted in imperfect crown segmentation. Thirdly, the analyses were performed using the entire city of Racibórz as a test site and it is uncertain how applicable the model parameterization is for other municipalities. Analyzing other municipalities with different tree species composition and geographic/meteorological conditions would require adjustments of model parameterization. Controlling these factors in future work would offer validation of the approach and explore its applicability under other conditions and tree species compositions.

Automatic detection of tree species using advanced aerial hyperspectral (HS) imaging would be beneficial. HS imaging may offer, for

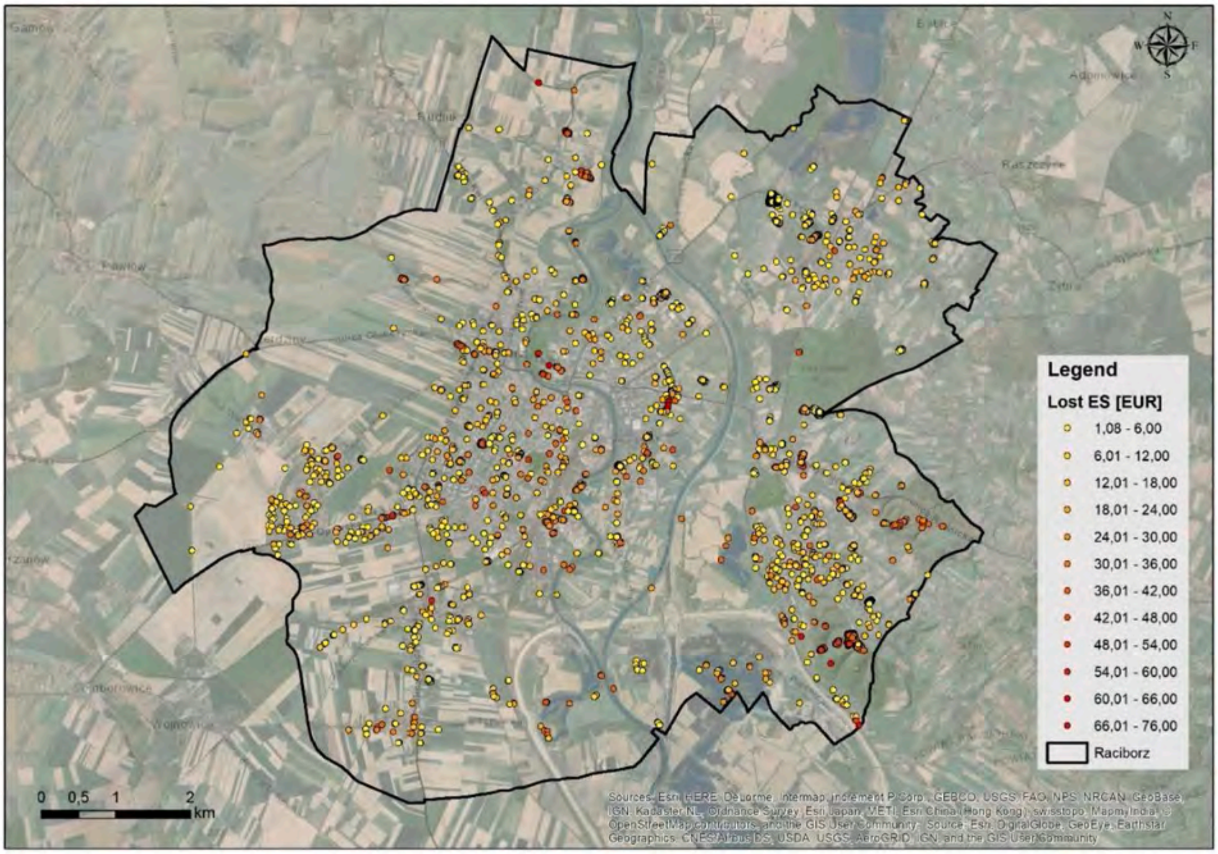

Fig. 10. The structural value of ecosystem services lost due to trees felled during the suspension of mandatory permits in Racibórz in 2017.

Table 5
Lost ecosystem services and their value attributable to trees felled in Racibórz from January 1 to March 5, 2017.

Genus	Carbon storage		Gross carbon sequestration		Pollution removal		Oxygen production	Avoided runoff	
	[Mg]	*[€]*	*[Mg/yr]*	*[€/yr]*	*[Mg/yr]*	*[(€/yr]*	*[Mg]*	*[m^3/yr]*	*[€/yr]*
Acer sp.	205	31 435	10	1 590	0.3	23 298	28	393	688
Tilia sp.	95	14 682	5	763	0.2	13 863	13	234	409
Fraxinus sp.	92	14 102	4	675	0.1	8 802	12	148	260
Total	**393**	**60 220**	**19**	**3 029**	**0.6**	**45 964**	**53**	**776**	**1 358**

example, over 200 spectral bands, thanks to which good accuracy of tree species identification can be achieved (e.g., 83 % accuracy by Alonzo et al. (2015) and 88.9 % by Zhang et al. (2016)). Recently, the use of Unmanned Aerial Vehicles (UAVs) to obtain high-resolution imagery, often using multiple spectral channels, is slowly becoming common practice in urban forest inventory (Näsi et al., 2018). These technologies require algorithm generation using very accurate data collected traditionally by arborists, supported by GNSS techniques for determining the position of trees or their biometric features, using TLS (Terrestrial Laser Scanning) or the increasingly popular MLS (Mobile Laser Scanning) (Wężyk et al., 2015; Warchoł et al., 2016) and HLS (Hand-held Laser Scanning). Point clouds obtained in this way offer unprecedented density, reaching several hundred or even several thousand points per square meter. For comparison, the ALS point cloud density used for the Racibórz study was approximately 12 pts/m^2 (Wężyk et al., 2019; Vepakomma and Cormier, 2019). These approaches can minimize the problems of obtaining precise geodata, making it possible to carry out assessments at any time and in a form adapted to the needs of the analysis to be performed.

In future, very dense LiDAR may replace fieldwork, especially for inventory of large cities. So far, 3D point clouds have not been implemented on a wide scale in urban management and planning units because the approach requires a high-level of technical skill and a change in approach to spatial data management by municipalities.

6. Conclusions

Remote sensing data, particularly airborne laser scanning point clouds, have great potential to improve urban tree inventory and monitoring. Remote sensing technologies enable to cope with difficulties of conducting inventories within areas where physical access is limited, particularly on private property. As demonstrated in this study, field data collected in city parks and open green areas combined with ALS data enables wall-to-wall estimation of urban forest ES, including private properties. While there will always be a need for field-based urban ecosystem analyses, remote sensing data greatly increase the breadth of questions that can be asked and the specificity, reliability, and extensiveness with which those questions can be answered. The proposed approach showed that change detection and the estimation of basic tree biometrical attributes using ALS point clouds and aerial, high-resolution CIR orthophotos significantly supplement information from tree field surveys and enable accurate assessment of ES losses. This has substantial potential to provide information to support urban greenery inventories and for monitoring selected ES provided by the urban forest. Our investigation revealed the potential for semi-automation of data compilation to estimate and detect ES losses caused by tree removal. Utilizing the proposed approach in different cities will require reparameterization of the algorithms used, to account for differences in vegetation structure and species composition. Valuable information on the use of these methodologies can be obtained by testing these or similar approaches in other cities. The methodologies can lead to the development of more universally applicable predictive models of future ES, which can be applied on a larger scale. The integration of various types of remote sensing and administrative data provides an approach to assess losses suffered by city residents due to unregulated urban tree cutting. The fusion of field inventory data and other GIS information with ALS and aerial digital orthophotos is a viable alternative to large scale field measurements, allowing assessment of ES for entire cities. We believe that municipal administrations will be increasingly inclined to use ALS point clouds to manage urban green areas as access to this type of spatial geodata increases. A hybrid method involving the use of advanced algorithms for machine learning fuzzing and ALS LiDAR point clouds can offer benefits in urban green infrastructure management.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgments

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