Summary

Monitoring changes in urban forest (UF) is a crucial task in the context of sustainable management in urban areas. Obtaining consistent information on the current status as well as on the changes and dynamics of UF is challenging due to the high heterogeneity, rapid and unpredictable changes of vegetation in the urban environment (e.g. owing to the lack of legislation on protection and felling of urban trees or the occurrence of temporary legal fluctuations in this field) and its high share in private land. Modern urban forest inventory and monitoring methods are increasingly supported by laser scanning (LiDAR), digital photogrammetry, aerial and satellite remote sensing technologies as well as mobile GIS (Geographic Information System) applications

The aim of this dissertation was to develop and analyse spatial indicators in a multidimensional approach, i.e. two-dimensional (2-D) and three-dimensional (3-D) using geo-information technologies, to identify changes in urban forests. Spatial indicators based on the fusion of 3-D UF volume information with landscape metrics (LM) and ecosystem services (ES) indicators were proposed. This dissertation focused on determining the utility of multi-temporal, multi-source and multi-resolution remote sensing imagery and 3-D point clouds derived from Airborne Laser Scanning (ALS LiDAR) time series for the detection of urban forest changes. A methodology was developed to fuse remote sensing data with field measurements to establish selected biometric parameters of urban trees (diameter at breast height - DBH and tree species/genus) and to estimate the ES provided by trees, as well as to assess their loss due to urban tree removal. By using geoinformation technologies, the effectiveness of tree protection legislation on private land was also examined, by comparing it with administrative decisions authorising tree removal.

The research objects were the urban forests of Krakow, Raciborz and Luxemburg. Reference data that were used for parameterization and accuracy assessment of the tree crown segmentation algorithm and for the correct determination of the proportion of individual tree species were collected on 41 sample plots (0.4 ha) in Racibórz, and a database with precise tree measurements from 3 parks in Krakow (ZZM Krakow) was used. Geographic Object-Based Image Analysis (GEOBIA) based on HR (High Resolution) satellite imagery: RapidEye with a spatial resolution of 5.0 m GSD (Ground Sampling Distance) and VHR (Very High Resolution) satellite imagery: IKONOS-2, QuickBird-2, WorldView-2 (GSD < 1.0 m), and aerial orthophoto maps (RGB/CIR composition; GSD < 0.25 m) both at specific time and in the ALS LiDAR point cloud, was used to determine the area of UF, vegetation distribution (low, medium, high) and to detect changes in the canopy cover. Vegetation volume was estimated using voxels (3-D pixels) generated from ALS LiDAR point clouds to create 3-D indices: Vegetation 3D Density Index (V3DI) and Vegetation Volume to Building Volume (VV2BV). The appropriate landscape metrics were then selected to quantify differences between vegetation structures obtained from the 2-D and 3-D approaches and to detect changes.

The obtained research results indicated that the spatial resolution (GSD) of multispectral remote sensing imagery increases the accuracy of GEOBIA analysis conducted in a complex urban environment. In the case of the high vegetation classification, the Kappa coefficient was 83%, when using 5 spectral bands (RapidEye, Planet) and a normalized Digital Surface Model (nDSM). At the same time, the classification accuracy of land cover maps was found to increase to 90% when using geodata fusion, i.e. a digital CIR orthophoto map (0.2 m GSD) and the ALS LiDAR point cloud (density > 12 points /m^2). As a result of tree crown segmentation based on very high-resolution imagery (VHR), a relatively high correlation was observed between the number of segments (GEOBIA) and the reference number of trees counted in the sample plots (R^2 = 0.86; MAPE = 21.1%). The developed methodology resulted in small mean percentage error (MPE = 0.3%) of estimates of the number of trees. The predictive model for DBH ($d_{1.3}$) developed on the basis of reference data from Kraków showed a value of R^2 = 0.67 for the data in Racibórz. By using landscape metrics based on time series analysis of remotely sensed data, it was possible to investigate the dynamics of changes occurring in heterogeneous urban forests. Measures of landscape connectivity derived from 3-D models showed lower values than those obtained from the 2-D approach. The omission of information on the vertical structure of vegetation leads to distortion of LM measures which hinders the monitoring of changes occurring in the UF area. The proposed 3-D spatial metrics may support the formulation of recommendations for optimal and equitable shaping of urban greenery distribution in the context of existing or planned building volume, indicating new appropriate directions of sustainable urban development. These results are particularly relevant for urban systems, where the spatial distribution of urban forests is crucial for the provision of ecosystem services.

Keywords: urban forests (UF), spatial metrics, 3D greenery monitoring, voxel, change detection, ecosystem services (ES), LiDAR point clouds, GEOBIA, remote sensing, GIS.