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High-precision monitoring of urban structures to understand changes in multiple ecosystem services

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ABSTRACT

To safeguard the well-being of urban dwellers, it is vital to restore, protect and enhance urban green infrastructures (uGI), their related ecosystem services (ES) and the associated benefits for a large number of inhabitants. This study maps and monitors land cover between 2012 and 2018 in the fast-growing German city of Leipzig to produce precise information using OBIA and very high-resolution digital orthophotos. Based on this, this research pinpoints spatially differentiated multiple ES. Research has revealed that essential ES, which comprise regulating, socio-cultural and cultural-aesthetic services, have a multifunctional impact on the human urban habitat. The study provides insight into each ES type by evaluating specific classes of objects within the urban environment in a spatially explicit way and at a very high scale of resolution. In doing so, it illustrates variations in the provision of ES and renders visible disparities in the accessibility to uGI in Leipzig. By analysing the number and stands of trees and their respective height development, the study confirms that intensive management is successfully rejuvenating the urban forest, but also that foliage in this forest is suffering from drought. The mapping procedure reveals a high spatial and temporal variation in the rates of carbon storage. This is also the case for the provision of recreation areas which has an impact on the equitable distribution of ES to Leipzig's inhabitants. Residential areas with a relatively high uGI on the outskirts of the city actually register lower market rents and rent growth rates than in those districts which lie closer to the city centre and have a comparably lower uGI. Thus, market rents and uGI have become decoupled in the fast growing city. In order to ensure and maintain the well-being of all residents in a fair way, fast growing cities like Leipzig must make even greater efforts in urban planning.

1. Introduction

The steady increase in urbanisation leads to the densification and expansion of urban areas worldwide. Today, Europe is one of the most heavily urbanised continents in the world with around 74% of its inhabitants living in urban areas (UN, 2018; UN Habitat, 2020). As the process of urbanisation advances, projections for 2050 assume that 84% of the total European population will live in cities (ibid.) by that date. These trends are accompanied by a greater expansion in an unbalanced use of land driven by the economic incentives of urban development. Studies have revealed that 59% of cities are also experiencing an increase in land use per new resident (Eurostat, 2018; Valentina et al., 2019). This situation encourages the construction of housing and public infrastructure, consequently creating denser and more dispersed urban areas. This in turn leads to the eradication or fragmentation of ecosystems and urban Green Infrastructure (uGI) and their related ecosystem services (ES) (Bagan et al., 2019). The New Urban Agenda (United Nations, 2017) recognises the need for the sustainable use and management of land and natural resources and is working to prevent unnecessary changes in land use. In urban areas, human inhabitants have an important connection to nature. Urbanites have a vast demand for ES and, simultaneously, elicit a huge impact on the environment (Elmqvist et al., 2015). The concept of the green city (Breuste, 2020) aims to protect and regenerate endangered ecosystems and to promote ES where green and blue infrastructure can ameliorate stressful environmental conditions. UGI is fundamental to delivering quality of life and sustainability in cities, especially with regard to trees and green spaces (Hansen et al., 2019).

1.1. The value of multiple ecosystem services

The value of uGI as a provider of multiple ES for the entire urban

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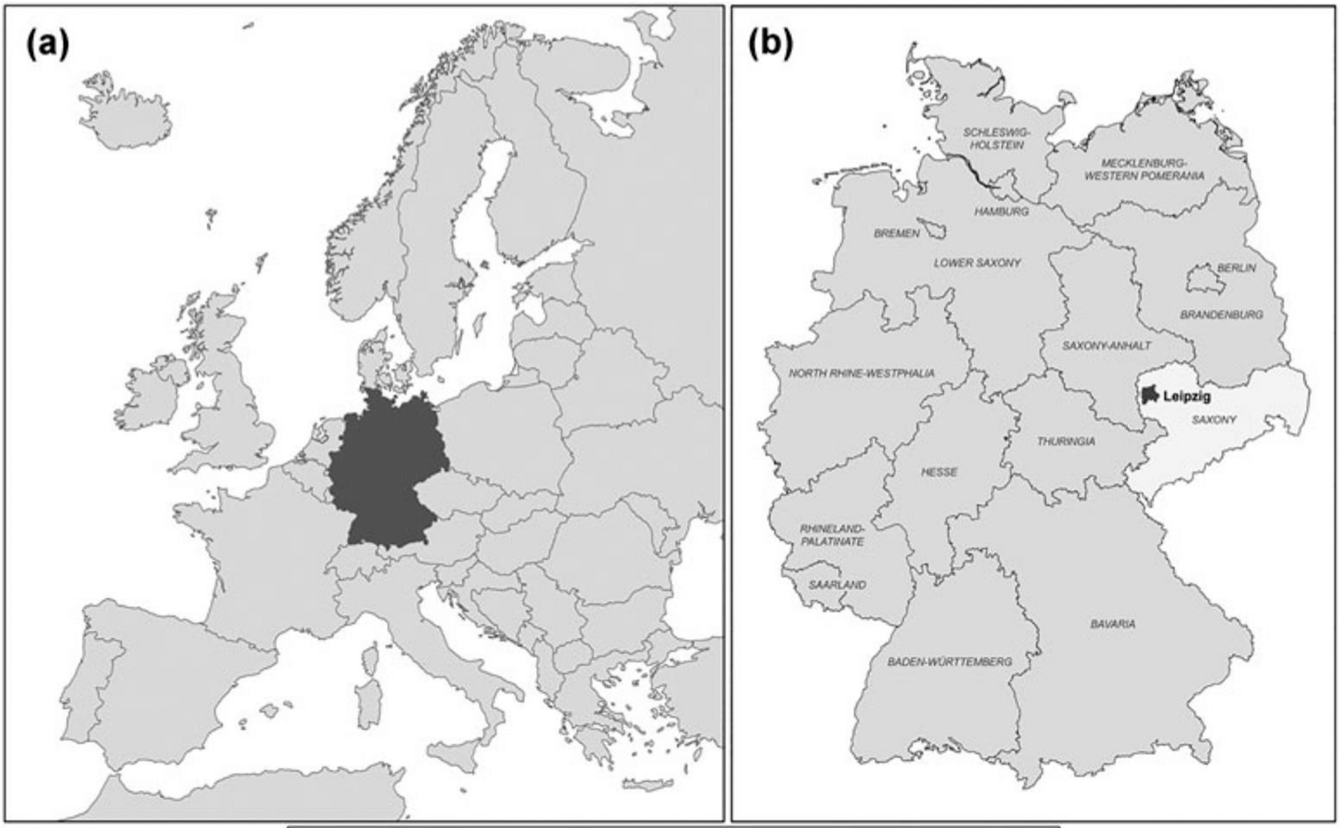


Fig. 1. Location of Germany in Europe (a) and the study area within Germany (b).

habitat has already been widely acknowledged (Lovell and Taylor, 2013; Salmond et al., 2016; United Nations, 2017). It comprises the reduction of potentially harmful exposures such as mitigating air pollution, decrease the urban heat island effect, and help contain inundations. Beyond, uGI and related ES foster human capacities by creating opportunities for physical activity and social interaction and restore capacities through spaces for recreation, and the aesthetic contributions to quality of life (Cox et al., 2017). For example, a stand of trees delivers cooling and shade at hot days, improves ambient air quality thanks to capturing airborne pollutants, enhances interception and serves as food source for birds and insects, whereas socio-cultural ES in recreation areas and urban woodland reduce stress. All these multiple ES benefits are closely linked to the local factors that influence the quality of life in a city (Jaganmohan et al., 2016; De la Barrera and Henríquez, 2017).

There is a need for monitoring approaches, which explicitly recognise the natural components and processes which underpin the evolution of uGI and related ES. Consequently, these aspects have been mapped and quantified for various cities across the globe at urban scale (Roy et al., 2012; Mills et al., 2016; Rodriguez-Valencia and Ortiz-Ramirez, 2021).

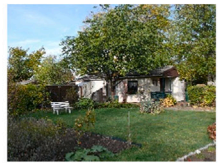
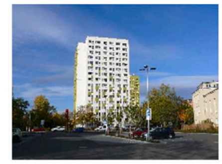
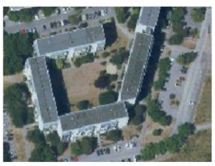
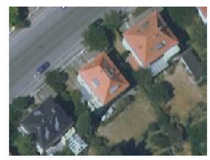
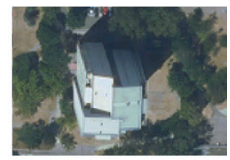
A crucial aspect is the time dimension: urban dynamics have a significant impact on the provision of green open spaces especially on the amount and distribution of urban-tree coverage, to name a significant ES feature. Maintaining or even enhancing multiple ecosystem services across an urban area demands for the analysis how consistently these services are generated by different land cover types over years (Gómez-Creutzberg et al., 2021). Such analytical investigations may suffer from constraints by high-resolution data availability across the area or for various time slots.

Research is now focusing on addressing the location-based differentiation of these benefits and qualities to secure ES within cities in a well-distributed way over time (Grêt-Regamey et al., 2013; Klopp and Petretta, 2017).

1.2. Urban remote sensing techniques to map and monitor urban structures

Mapping the ecological effects of urbanisation processes deepens our understanding of the varying intensity of ES. For fast-growing cities, it is important to record critical urban dimensions that are relevant to human well-being (Simon et al., 2016), especially as the ongoing process of urbanisation goes hand in hand with changes in land cover (Zawadzka et al., 2020). Variations within cities are largely unexplored at high resolution but they are necessary to capture the heterogeneity of urban ecosystems and their services (Steele and Wolz, 2019). However, merely mapping built land and interspersed natural spaces in high proximity is a rather static activity. Monitoring pertinent processes appears to be a much more effective tool to help understand the urban dynamics and measure the degree to which sustainable urban development is being attained or missed over time (UN-Habitat, 2018; UN GGIM, 2019). In this context, we apply spatial monitoring via geospatial data to visualise development processes related to indicators in a spatially explicit way and provide evidence of such processes over a specific time period as requested by UN (UN GGIM, 2019). Our approach is in line with the New Urban Agenda (ibid.) that promotes data collection and mapping to monitor urban development and implement a spatial-monitoring system in order to capture the ecological functions of land. Related indicators can clarify rather complex processes with regards to urban inhabitants and their demand for ES. Only by setting the urban dynamics in context with the supply and demand of ES at a neighbourhood level we render potential imbalances visible. This study undertakes a mapping and monitoring approach that allows a deeper, spatially explicit investigation into the effects of processes that may hinder sustainable urban development. Only by fostering the development of healthy, low-carbon, resource-efficient and liveable urban spaces may we succeed in harnessing the dynamic processes which build resilient cities (Kabisch et al., 2017).

Table 1
Dominant building types in Leipzig.

Linear housing	Perimeter blocks	Bungalows and garages	(Semi-)detached houses	High-rise buildings
		Street view		
				
(a)	(b)	(c)	(d)	(e)
		Bird's eye view		
				

Source:Sources: Street view photos (©Ellen Banzhaf); bird's eye view by DOPs (Staatsbetrieb Geobasisinformation und Vermessung Sachsen (2019).

Table 2
Air temperature and precipitation data for 2012 and 2018 (Stadt Leipzig, 2021b).

	2012	2018
Days with temperatures > 30 °C	10	29
Days with temperatures > 25 °C	44	56
Annual precipitation	468 mm	338 mm
Variance from average precipitation (511 mm)	-8.4%	-33.9%

When undertaking spatial analysis over time, this study relies on effective remote-sensing techniques. For urban areas very high resolution (VHR) data are of high priority as the knowledge provided by a highly precise and spatial urban-area mapping exercise is essential for successful urban planning. Various degrees of homogeneous and heterogeneous pattern of urban land cover can thus be located and quantified and set in context with demands and supply by ES. Built-up structures as well as different green structures, especially lawn/ meadows, scrubland and trees, are shed light to regarding environmental as well as socio-economic characteristics that signify urban liveability.

The advantages of airborne and spaceborne VHR imageries lie in their increasing availability, while spatial and spectral resolution also increases. This study profits from the OBIA approach and applies it in a sophisticated way. During the past decade, new methods and technologies such as object-based image analysis (OBIA) have become established and further developed. Thanks to its manifold applications, OBIA has now taken precedence over pixel-based methods of detailed urban-area research (Banzhaf and Höfer, 2008; Banzhaf et al., 2020). Although OBIA is time consuming and demands greater computational power than more traditional, pixel-based approaches, between 1980 and 2019 the number of studies using OBIA increased from 0% to 32% (Lourenço et al., 2021; Reba and Seto, 2020). OBIA can be used for various strands in research, e.g. to foster a detailed understanding of urban green spaces (Baker and Smith, 2019; Shekhar and Aryal, 2019) or for local climate-zone mapping (Simanjuntak et al., 2019). Using this type of remote-sensing technology, this study aims to address the following research questions:

1. How robust is the spatial configuration with regards to urban-growth processes?
2. How do the different types of urban ES visualise urban-growth processes at the local level?
3. Are existing ES benefits well distributed in the urban area?

We will monitor multiple ES types of provisioning, thus exemplifying regulating and socio-cultural services to understand the correlation between them and the urban structure. This is intended to raise awareness about the local characteristics of an urban area, because the neighbourhood scale plays a central role in the dynamic process of building resilient cities (United Nations, 2017).

2. Data and Material

2.1. Study area

The European-based 2007 Leipzig Charter was adapted in 2020 to take into account new challenges such as climate change, the experience of a pandemic and the loss of biodiversity. The New Leipzig Charter provides a policy framework that can envision and realise European and global agreements at an urban scale. Implementing the new Leipzig Charter will contribute to establishing a more impactful Urban Agenda for the EU (Bundesministerium des Innern, für Bau und Heimat, 2020). It comprises the three dimensions of social justice, ecological awareness and productivity based on a compact and polycentric city. This study examines some of the preconditions exemplified by the city of Leipzig (Fig. 1). Another reason for choosing Leipzig is because it is one of Europe's most dynamic cities and was the fastest growing city in Germany during the last decade. Its population increased by almost 23% from 493,200 inhabitants in 2000–605,400 in 2020 (Amt für Statistik und Wahlen der Stadt Leipzig, 2021). Such a large population growth necessitates significant structural changes and confirms Leipzig as a valuable research subject.

Leipzig covers an area of 297 km^2 and is divided into 63 local administrative districts. These differ in their historical and residential development: while some neighbourhoods are dominated by perimeter blocks dating back more than 100 years, others feature linear housing supplemented by high-rise buildings from the 1960–1980 s. Estates of single-family houses are a feature of the 20th century where they originated in the 1920 s as garden suburbs. In the last 20 years, this type of housing has enjoyed a resurgence in popularity as part of the redensification of former brownfield sites and large open spaces. Table 1

Table 3
Input data for the 2018 Leipzig mapping.

	DOP	DSM
Acquisition date	7 July 2018	13/14 February 2018
Spatial resolution	0.2 m	2 m in x, y and 0.15 m in z direction
Spectral resolution	VNIR	single band

contains examples of each of the five predominant building types in Leipzig from both a street and bird's eye view. A special natural area is provided by the alluvial forest which functions as the city's green lung and runs through Leipzig in a south-north and then northwest direction. Moreover, comprising 30% of Leipzig's green area, allotment gardens afford a significant amount of green space with 278 allotment associations covering an area of 1,200 ha in total (Stadt Leipzig, 2021a).

Table 2 illustrates selected climate data for Leipzig for the two time periods and the average amount of precipitation. The area is characterised by a long-term low precipitation rate of 511 mm per year (meteorological mean for 1961–1990; Stadt Leipzig, 2021b). In July 2018 Leipzig, like most Central European regions, was hit by a heatwave-induced drought. A decrease in precipitation and higher temperatures can be observed in the climate-dependent ES; these are analysed and discussed in Section 4.

2.2. Input data for ES mapping and monitoring

The classification process involved several airborne raster images as well as vector data. The spectral information originates from a digital orthophoto mosaic (DOP) acquired by the Ordnance Survey of the state

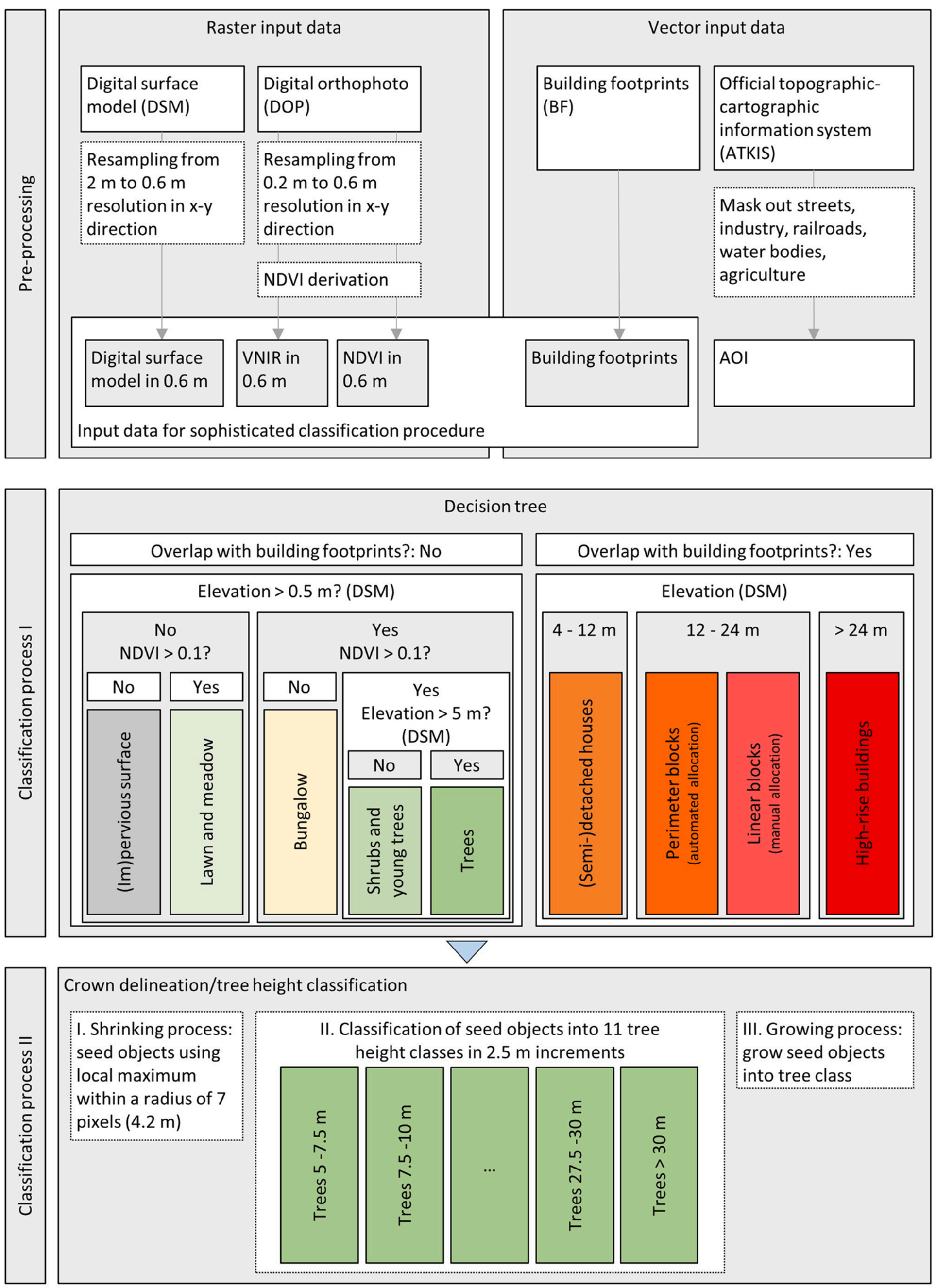


Fig. 2. Flowchart of OBIA mapping procedure (Pre-processing and Classification process I) and generation of height-discriminating tree cover (Classification process II).

Table 4
Class definitions.

Class name	Class description	Height above ground [m]
Grey structures		
Bungalows and garages	Single-storey building	2 to < 4
(Semi-) detached houses	Multi-storey family house (2–3 storeys, post-1900)	4 to < 12
Linear housing	Long lines of linear residential housing with flat roofs (prefabricated houses, 1960–1989)	12 to < 17
Perimeter blocks	Closed-block developments with gable roofs (mostly Wilhelminian style, 1870–1920)	17 to < 24
High-rise buildings	Multi-storey residential housing (mainly prefabricated houses, 1960–1989)	≥ 24
(Im)pervious surface	No vegetation cover, no building	0
Green structures		
Lawn/grass	Homogeneous structural segment	< 0.5
Shrubs/young trees	Heterogeneous vegetation segments	> 0.5 to < 5
Trees	Heterogeneous vegetation segments	> 5 m to 7.49
Trees	Heterogeneous vegetation segments	7.5 m to 9.99
…		….
Trees	Heterogeneous vegetation segments	> 30

of Saxony in 2018 (Table 3) (Staatsbetrieb Geobasisinformation und Vermessung Sachsen, 2019). The sensor acquires orthophotos at a spectral resolution of four bands in the visible and near infrared range (VNIR) and allows a spatial resolution of 0.2 m x 0.2 m ground resolution. As the Saxon Ordnance Survey has a three-year-repetition rate, and a subsequent data processing of more than half a year, the most recent data was acquired on 7 July 2018. The normalized digital surface model (nDSM) is provided by the same Ordnance Survey and stems from a LiDAR acquisition, dated 13 and 14 February 2018. Based on the subtraction of a digital elevation model (ibid.), the nDSM contains the absolute elevation values. While the spatial resolution in the x and y-dimensions is 2 m x 2 m, the accuracy in the z-direction is 0.15 m (Staatsbetrieb Geobasisinformation und Vermessung Sachsen, 2019).

Furthermore, two vector datasets from the German authorities were used to support the analysis (Bundesamt für Kartographie und Geodäsie, 2018): (i) the official topographic-cartographic information system (ATKIS), and (ii) building footprints. While ATKIS contains detailed functional information about underlying urban structures, the building footprints comprise the polygon footprints of all the residential buildings in the administrative area. These vector datasets are provided on an annual basis; the study uses the 01/2018 dataset (Staatsbetrieb Geobasisinformation und Vermessung Sachsen, 2019).

Additional input data from the 2012 mapping originates from an earlier piece of research (Banzhaf et al., 2020) and enables the LULC mapping to be monitored with a six-year interval. However, for the 2012 mapping procedure the nDSM was captured in 2010, while the DOP stems from 2012. Thus, a time span of eight years must be considered when monitoring tree growth.

3. Methods

3.1. OBIA classification process and class depiction

In contrast to pixel-based approaches, which consider each pixel and its spectral properties independently, the object-based image analysis (OBIA) first segments the underlying ground into object units bearing similar properties. Further information is then gained about these objects by generating their shapes, textures and neighbourhood relationships. OBIA makes it possible to delineate environmental structures from remotely obtained data with a very high spatial resolution (Hajek, 2005; Lu et al., 2014).

As depicted in Fig. 2, the classification process is divided into three stages. In the pre-processing stage, all the raster-input data is resampled to a uniform x-y resolution of 0.6 m to correspond with the previous classification (Banzhaf et al., 2020). Moreover, vector data from ATKIS is masked to reduce misclassification and ease the demand on computation. To enable a comparison with the OBIA classification from 2012 to be made, the number and definition of the main classes of data were predefined (Table 4). The classification includes five building classes, of which four indicate residential usage. Moreover, it comprises three classes of vegetation as well as the (im)pervious class. Classes of non-residential land usage/land cover (LULC) which registered little change, including streets, railway structures, industrial buildings, bodies of water and agricultural land, were not included in the analysis.

Classification Process I is OBIA-based and follows a decision tree. First, objects matching the building footprints are further classified into the four residential building classes based on their absolute elevation. Non-compliant objects are then additionally classified by their height into elevated (> 0.5 m) and non-elevated objects (< 0.5 m). The latter are subdivided into (im)pervious surfaces and lawn/grass by using an NDVI threshold of 0.1. Elevated objects are also classified by the NDVI threshold into bungalows/garages and trees. The latter are then subclassified by their height into shrubs/young trees < 5 m and mature trees ≥ 5 m as defined by the EEA (European Environmental Agency, 2021). During Classification Process II, a height discrimination calculation is undertaken to differentiate trees by their height on a pixel by pixel analysis (Section 3.2.1). This process was not only undertaken for the 2018 data but retroactively for the data set from 2012 to allow a distinct monitoring evaluation.

Table 5
Accuracy assessment for the mapping result in 2018.

Class names	NB	IS	LG	ST	TR	BU	SD	PS	PB	HR	Producer's accuracy [%]	User's accuracy [%]	j
NB - Non-functional buildings	–	–	–	–	–	–	–	–	–	–	–	–	
IS - (Im)pervious surface	1	90	5	–	–	2	–	–	2	–	89.1	90.0	0.90
LG - Lawn/grass	–	2	95	1	–	1	1	–	–	–	88.0	95.0	0.95
ST - Shrubs/young trees	–	4	7	87	–	2	–	–	–	–	96.7	87.0	0.87
TR – Trees	–	–	–	2	95	–	–	1	2	–	100.0	95.0	0.95
BU - Bungalows and garages	–	4	–	–	–	94	2	–	–	–	90.4	94.0	0.94
SD - (Semi-)detached houses	–	1	–	–	–	4	85	4	5	1	92.4	85.0	0.84
LS - Linear housing	1	–	–	–	–	1	1	92	5	–	87.6	92.0	0.92
PB - Perimeter blocks	9	–	–	–	–	–	3	8	80	–	84.2	80.0	0.79
HR - High-rise buildings	1	–	1	–	–	–	–	–	1	97	99.0	97.0	0.98
											Overall Classification accuracy 90.6%		Kappa statistics 0.89

Table 7
Link between average green space cover and offer rent.

Local district	Average rent in 2012	Average rent in 2018	Absolute rent difference	Average area of green spaces in a 300 m radius in 2012	Average area of greenspaces in a 300m radius in 2018	Difference in average green spaces in a 300 m radius	Index of market rent to green space in 2012	Index of market rent to green space in 2018
	[€]	[€]	[€]	[ha]	[ha]	[ha]	[€/ha]	[€/ha]
Zentrum-West	6.21	8.22	2.01	12.4	10.9	-1.4	11.5	10.1
Zentrum-Südost	5.75	9.06	3.31	10.5	10.0	-0.5	9.6	9.3
Zentrum-Süd	6.54	8.58	2.04	12.0	10.0	-2.0	11.2	9.2
Zentrum-Ost	6.10	9.38	3.28	8.3	6.8	-1.5	7.4	6.1
Zentrum-Nordwest	6.30	8.10	1.80	14.1	12.4	-1.7	13.3	11.6
Zentrum-Nord	5.58	7.84	2.26	10.2	7.1	-3.1	9.3	6.3
Zentrum	7.12	8.90	1.78	4.2	4.0	-0.2	3.5	3.2
Wiederitzsch	5.39	6.72	1.33	17.1	14.7	-2.4	16.2	13.7
Wahren	5.06	6.55	1.49	17.4	15.3	-2.2	16.4	14.2
Volkmarsdorf	4.32	6.67	2.35	12.9	10.5	-2.4	11.7	9.5
Thekla	4.98	6.49	1.51	18.7	14.9	-3.8	17.7	13.9
Stötteritz	5.03	6.89	1.86	17.6	14.8	-2.8	16.6	13.8
Sellerhausen-Stünz	4.75	6.31	1.56	17.2	15.2	-2.0	16.1	14.1
Seehausen	5.31	7.04	1.73	13.4	10.4	-3.0	12.4	9.5
Schleußig	5.73	7.81	2.08	16.4	14.6	-1.8	15.5	13.7
Schönefeld-Ost	4.75	5.91	1.16	16.2	13.0	-3.2	15.1	11.9
Schönefeld-Abtnaundorf	4.78	6.22	1.44	15.1	12.5	-2.6	14.0	11.4
Schönau	4.32	7.11	2.79	16.2	13.6	-2.7	15.0	12.6
Südvorstadt	5.96	8.43	2.47	12.0	10.4	-1.6	11.2	9.6
Reudnitz-Thonberg	5.13	6.99	1.86	12.7	10.5	-2.2	11.6	9.5
Probstheida	5.31	6.35	1.04	18.3	15.5	-2.8	17.3	14.4
Plaußig-Portitz	5.32	6.72	1.40	15.6	13.3	-2.3	14.7	12.3
Plagwitz	5.50	7.54	2.04	9.4	7.5	-1.9	8.4	6.6
Paunsdorf	4.45	5.74	1.29	15.7	13.6	-2.1	14.6	12.4
Neustadt-Neuschönefeld	4.57	6.58	2.01	11.0	9.6	-1.4	9.9	8.5
Neulindenau	5.15	6.64	1.49	14.0	9.4	-4.7	13.0	8.3
Mockau-Süd	4.89	6.28	1.39	16.2	13.8	-2.4	15.1	12.7
Mockau-Nord	4.91	5.83	0.92	19.0	17.6	-1.4	17.9	16.4
Miltitz	5.18	6.25	1.07	15.7	13.9	-1.8	14.7	12.8
Meusdorf	5.12	6.73	1.61	18.3	16.9	-1.3	17.3	15.9
Marienbrunn	5.32	6.60	1.28	16.6	15.8	-0.8	15.6	14.7
Mölkau	5.57	6.92	1.35	16.1	14.0	-2.1	15.1	13.0
Möckern	4.91	6.85	1.94	17.8	15.2	-2.5	16.7	14.2
Lindenthal	5.34	6.74	1.40	15.2	12.4	-2.8	14.2	11.4
Lindenau	5.10	7.32	2.22	10.7	9.0	-1.7	9.7	8.1
Liebertwolkwitz	5.48	6.63	1.15	13.0	11.0	-2.0	12.1	10.0
Leutzsch	4.92	6.56	1.64	17.2	14.7	-2.6	16.2	13.6
Lausen-Grünau	4.09	5.67	1.58	16.8	15.5	-1.3	15.5	14.3
Lützschena-Stahmeln	5.17	7.43	2.26	15.7	12.3	-3.4	14.7	11.4
Lößnig	5.11	6.38	1.27	15.7	13.7	-2.0	14.7	12.6

(continued on next page)

Table 7 (*continued*)

Knautkleeberg-Knauthain	5.91	7.49	1.58	14.8	13.2	-1.5	13.9	12.3
Kleinzschocher	4.81	6.57	1.76	16.6	13.0	-3.6	15.5	11.9
Holzhausen	5.23	6.26	1.03	14.8	12.4	-2.4	13.8	11.3
Heiterblick	5.92	7.10	1.18	15.7	14.9	-0.8	14.9	14.0
Hartmannsdorf	5.42	n.a.	n.a.	13.1	n.a.	n.a.	12.1	n.a.
Großzschocher	4.93	6.45	1.52	16.6	13.3	-3.3	15.6	12.2
Grünau-Siedlung	4.60	5.88	1.28	17.3	16.2	-1.0	16.1	15.1
Grünau-Ost	4.77	5.46	0.69	17.6	16.5	-1.1	16.5	15.2
Grünau-Nord	4.24	5.44	1.20	16.5	16.5	0.0	15.3	15.3
Grünau-Mitte	4.26	5.45	1.19	16.5	16.3	-0.2	15.3	15.1
Gohlis-Süd	5.43	7.08	1.65	15.3	11.2	-4.1	14.3	10.2
Gohlis-Nord	5.16	6.66	1.50	18.9	16.1	-2.8	17.9	15.1
Gohlis-Mitte	5.50	7.19	1.69	13.2	12.4	-0.8	12.3	11.5
Eutritzsch	5.13	6.76	1.63	15.0	12.0	-3.0	14.0	11.0
Engelsdorf	5.37	6.37	1.00	13.9	11.6	-2.3	12.9	10.5
Dölitz-Dösen	5.30	6.60	1.30	17.7	15.4	-2.3	16.7	14.3
Connewitz	5.57	8.05	2.48	15.1	13.1	-2.0	14.2	12.2
Burghausen-Rückmarsdorf	5.47	6.66	1.19	14.3	12.5	-1.8	13.4	11.5
Baalsdorf	4.59	7.14	2.55	14.7	13.2	-1.5	13.5	12.3
Böhlitz-Ehrenberg	5.19	6.80	1.61	14.9	12.6	-2.3	13.9	11.6
Anger-Crottendorf	4.68	6.45	1.77	18.2	15.2	-3.0	17.1	14.1
Altlindenau	4.86	7.02	2.16	12.5	10.2	-2.4	11.5	9.2
Althen-Kleinpösna	4.80	5.95	1.15	12.3	9.6	-2.7	11.2	8.5

3.1.1. *Accuracy assessment*

An accuracy assessment was undertaken for the mapping in 2018. Each class was validated using 100 sample points whose locations coincided with the 2012 validation, once again using visual interpretation of Google Maps' imagery (Banzhaf et al., 2020). This guaranteed the most effective comparison between the data collected in 2012 and 2018. The allocations were then checked by hand for 900 sampling points (Table 5).

3.2. *Selected indicators to illustrate the main types of ES*

3.2.1. *Distinct tree cover by height differentiation (across main ES types)*

The location, quantity and coverage of urban trees are important factors to help estimate the enhanced environmental quality – such as cooling, shading, carbon sink, etc. – provided by ES in residential areas (Richter et al., 2020). Larger and more mature trees possess larger canopies and carry more biomass, thus providing a greater quantity of ES than smaller and younger trees.

Quantifying trees from above is a challenge. Due to the structure of tree crowns during the leaf-bearing seasons, it is almost impossible to distinguish single trees in a stand of trees when using VHR imagery alone. Nevertheless, the tree canopy cover is an assessable measure that can be used to quantify the total percentage of trees in a spatially defined urban area (Bristol Tree Forum, 2018). To enable more detailed analyses, Classification Process II is undertaken in two stages. Firstly, the maximum local elevations in a 5 m radius are searched within the areas categorised as belonging to the tree class in the previous classification procedure. Each local maximum is assumed to be the highest point of a tree. These points or pixels are then reclassified into eleven tree classes, starting with a class from $\geq$ 5–7.49 m and increasing in increments of 2.5 m up to the highest tree class of $\geq$ 30 m. Secondly, in the growing algorithm of the classified local maxima points, the objects grow pixel by pixel until they either reach the boundary of the original tree class or of another growing object. The combination of these complementary classification processes achieves the most effective extraction of information and therefore an optimal result.

3.2.2. *Carbon storage estimation (regulating ES type)*

Carbon capture and storage involves capturing, transporting, and storing carbon dioxide. Significant is the area of leaf coverage that strongly correlates to pollution capture and carbon sequestration (i.e. long-term capturing and storing of carbon dioxide); it is therefore an important indicator of regulating ES. Carbon storage is estimated using the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model developed by The Natural Capital Project (The Natural Capital Project, 2021). InVEST is set of tools to model the connections between nature and ES, like hazard protection and heat mitigation (Hamel et al., 2021). Many recent studies benefit from InVEST, from the local level (Maanan et al., 2019; Fekadu Hailu et al., 2021) up to the global level (Chaplin-Kramer et al., 2019). The value of this model toolbox is its ability to "simultaneously assess a large number of ES", even though it does not comprise the most sophisticated models (Hamel et al., 2021). In comparison with other models, it has been demonstrated, that InVEST generates reliable results and can keep up with more sophisticated models like LUCI (Land Utilisation and Capability Indicator) and ARIES (Artificial Intelligence for Ecosystem Services) (Sharps et al., 2017). In this study, we make use of InVEST to benefit from its simplicity that allows spatial allocation and quantification of carbon storage even if some input data like tree diameter is lacking.

Based on a LULC map, the model aggregates the carbon stored in four pools:

(i) above-ground biomass comprising all living plant material above the soil (e.g. tree bark, trunks, branches, leaves);
(ii) below-ground biomass including the living root systems;
(iii) the soil pool containing organic components within the soil;

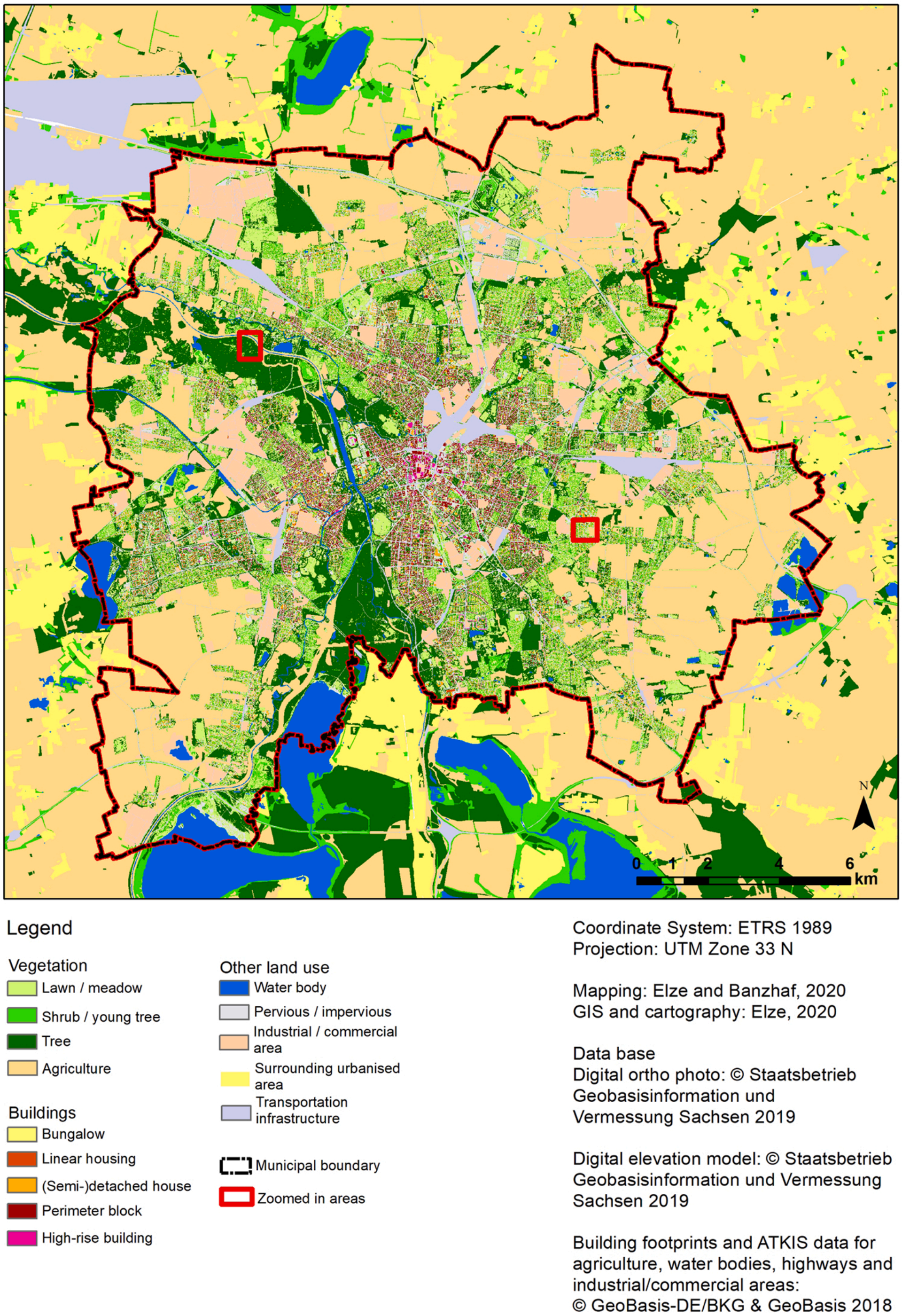


Fig. 3. OBIA land cover map of Leipzig. The area within the municipal boundary was classified using DOP and DEM/DSM from 2018 (Note: the red-bordered zoomed in-areas are depicted in Fig. 5 and Fig. 6).

(iv) the dead organic matter pool including organic litter as well as fallen and standing dead wood.

The carbon-pool values inputted for this InVEST model are laid out in the Appendix (Tab. A-1).

For each LULC class, at least one of the four pool values must be known while the remaining values are estimated by the model. The accuracy of the model improves with the input of individual, non-estimated pool values. In this study, the carbon-pool values are taken from Richter et al. (2020) for the LULC main classes and Klingenfuß et al. (2020) for the leaf coverage of all tree-height classes.

The carbon-storage model can cause confusion in the classified LULC map on the one hand; on the other, a drawback of the InVEST model is its over-simplification because carbon moving from one pool to another is ignored, and the carbon storage is assumed to be a linear process. The InVEST model only requires a LULC map and corresponding carbon-pool data and does not consider biophysical conditions such as photosynthesis rates and active soil organisms (The Natural Capital Project, 2021). This prerequisite was an advantage since we had no access to additional data including the species, age or trunk diameter of the trees. The InVEST model does present an added value since it enables intra-city differentiation of pollution capture.

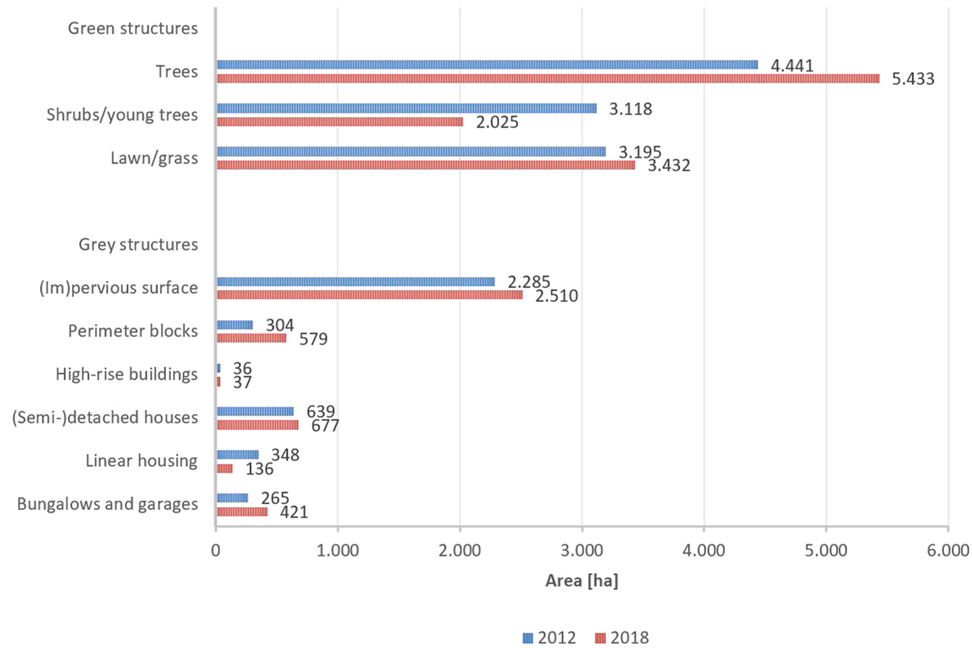


Fig. 4. Change detection of LULC classes in 2012 and 2018 (in hectares).

3.2.3. *Market rents related to green structures (socio-cultural ES type)*

Research indicates a key relationship between tree-canopy cover and social inequality (Mills et al., 2016, Iverson and Cook, 2000). We analysed this relationship by looking at market rents offered in Leipzig and how they have developed over time to test if there is a correlation between rental prices and local configuration with uGI and related ES.

Leipzig's city authority commissioned the Empirica consulting and research company to survey the city's property market. Empirica granted us access to their ongoing database relating to this survey for our study (VALUE Marktdaten, 2021). The database comprises information on more than 270,000 apartments in Leipzig, including their exact locations and rental costs. The so-called market rent is the amount of rent charged for equivalent properties on the market and is not necessarily the rent actually paid by residents. We calculated the average market rent per m^2 in a local district and then delineated the average share of green spaces in a 300 m radius around residential buildings in that district to investigate the potential influence of nearby green structures on this socio-economic variable (Annerstedt et al., 2016; WHO Europe, 2016). The distance in our proposed method is also a useful way to evaluate the influence of uGI on market rents. Working with both values, we were able to calculate an index for both years of the study to determine if there is a link between market rents and green spaces in the neighbourhood. We also calculated a proportionate index to normalise market rents and the average area of green space (Table 7).

Equ. 1: Calculation of the market rent – green space index (RG-Index)

$$RG - Index_{YEAR} = \frac{R_{LD} - R_{YEAR}}{G_{LD}}$$

R_{LD} Average market rent for the local district in a specific year.

R_{YEAR} Average market rent for Leipzig in a specific year.

G_{LD}Average area of green space for the local district in a specific year.

3.3. *Recreation areas (cultural-aesthetic ES type)*

As a representative of cultural aesthetic ES types, we determined the number of recreation areas in Leipzig and the changes they underwent. The city authority records geographical information about such areas in their official topographic-cartographic information system (Bundesamt für Kartographie und Geodäsie, 2018). While the 2018 dataset includes sports and recreation areas, a change in data management meant that these areas were split into three datasets in 2012. After filtering and merging both vector datasets, a spatial analysis between both years was undertaken to determine the number and spatial extent of these public spaces. Based on the results of our mapping process, we quantified the LULC changes within these recreation areas to understand a potential variation it their quality.

4. Results and discussion

4.1. *LULC mapping and change detection*

The OBIA classification presented in Fig. 3 provides an overview of the shape, spatial extent, land cover and structure of Leipzig in 2018. The image shows the large artificial lakes on the outskirts of the city, the alluvial forest running in a south-north and northwest direction, the city centre with a significant area occupied by the central train station and its railway tracks running northeast of the centre, the polycentric urban residential structures and the way in which the city is embedded in the surrounding agricultural landscape.

Table 5 reveals an overall accuracy of 90.6% (Kappa of 0.89) in the mapping exercise. Most confusion occurred within the building classes. The most inaccurately identified land-use class (with an accuracy of 84.2%) was the perimeter blocks. This was because of the likelihood of them being confused with non-residential buildings such as schools or churches. The most accurately identified classes were those of high-rise buildings and trees due to their height differentiation.

Fig. 4 illustrates the land-use area statistics. While vegetation classes comprise the largest share of land use, with almost 11,000 ha in 2018, fabricated grey structures comprise the largest share of (im)pervious surfaces at over 2,500 ha. The dry summer of 2018 led to a classification error occurring between lawn/grass and impervious structures due to the low-chlorophyll content of grassy vegetation at this time. The differences in area between linear housing and perimeter blocks was also affected by some confusion in classification. Differences of around 1,000 ha between the classes of mature trees and shrubs/young trees occurred due to tree growth, with young trees of an elevation of below 5 m in 2012 growing into the tree class of above 5 m in 2018 (see Section 2.2). Nonetheless, in 2018 the area of tree coverage is slightly underestimated due to drought stress resulting in sparser canopies, and should

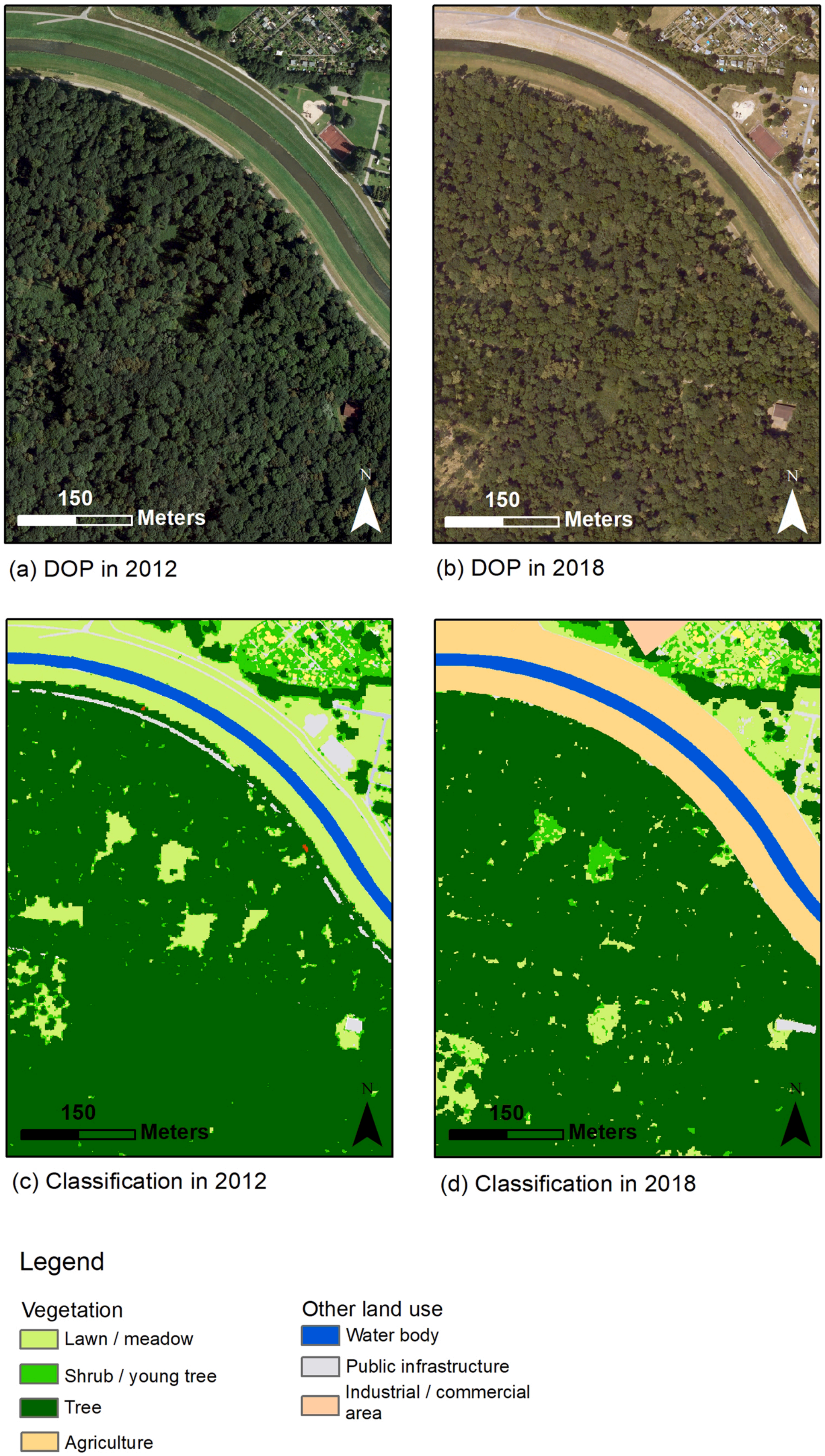


Fig. 5. Change detection of tree stands in the alluvial forest in the Burgaue and along the Neue Luppe river in northern Leipzig.

Fig. 6. Monitoring of changes from open spaces to residential areas with (semi-)detached houses between 2012 and 2018 exemplified in the local district of Mölkau.

be approximately at least 100 ha larger (see Table 2). This effect is discernible in Fig. 5(c) and (d): in 2018, the tree stand is less dense than in 2012 and the ground becomes visible.

In this study, therefore, not only a process of change is depicted. Yet, also the vulnerability of vegetation to drought is made visible (Fig. 5). As ES require vital vegetation for optimal availability, they provide services at a correspondingly reduced level in times of heat stress (Table A2).

The zoomed-in map (Fig. 5) reveals parts of the alluvial forest in the northwest of Leipzig. Besides the sparser and scattered tree crowns mentioned above, the tree cover is also reduced due to logging undertaken as tree management activity for the purposes of regeneration which registers a rejuvenation of tree cover in the managed urban forest. In future, the Department of Urban Green Areas and Watercourses in the Leipzig City Authority aims to restructure the urban forest to allow it to attain a more natural state with a higher biodiversity (Stadt Leipzig, 2021c). With regards to the European-based Leipzig Charter in 2020, it

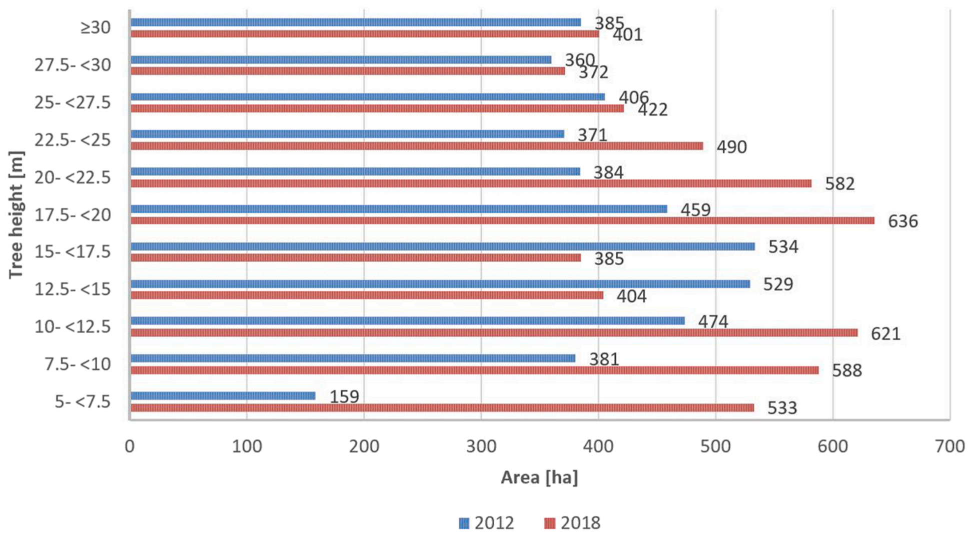


Fig. 7. Overall tree area statistics.

Table 6
Extremata of local districts with notable change in tree cover.

Local district	Total Area	Trees in 2012	Trees in 2018	Share in 2012	Share in 2018	Difference 2018–2012
	[ha]	[ha]	[ha]	[%]	[%]	[%]
Grünau-Nord	94.9	12.1	27.8	12.7	29.3	+ 16.5
Grünau-Mitte	123.7	17.7	34.3	14.3	27.7	+ 13.4
Gohlis-Nord	204.0	36.7	57.0	18.0	27.9	+ 9.9
Zentrum-Süd	156.3	41.8	40.6	26.8	26.0	-0.8
Gohlis-Mitte	129.3	25.5	25.2	19.7	19.5	-0.2
Gohlis-Süd	198.6	42.7	42.4	21.5	21.3	-0.1

is noted that the city of Leipzig is facing up to the challenges of climate change and is undertaking forest restructuring accordingly. Woodland productivity is thus more likely to be ensured in the long term.

Beyond that, additional changes in the LULC image include a large-scale construction along the riverside. After severe flooding in 2013, the northern meadow-covered dyke (in the 2012 image) was enlarged and a wall added, along with other measures which were still ongoing in 2018. This means that engineering designs must support regulating ES at this point to ensure protection from further flooding.

Another example of LULC change is shown in Fig. 6 for residential areas in the local district of Mölkau between 2012 and 2018 where a green space was cleared for a development of single-family houses. This development typifies densification processes – albeit at quite a dispersed level – initiated by planning measures taken to meet the demand of housing requirements while avoiding urban sprawl.

Fig. 6 depicts a specific process in a city witnessing a high pressure on land due to a large population increase in which densification occurs at the expense of open spaces, with preference given to single-family homes. It is also associated with the continuing prioritisation of (semi-)detached houses, meaning that although infill still takes place, it involves a lower number of residents and this causes a certain lack of density. This development is visualised in Fig. 6, yet it can be observed in various places in the urban area. Although the New Leipzig Charter, explained in Section 2.1, aims at implementing a compact city, the monitored change in urban built structure cannot confirm that the city has moved closer to the target during this period. This is especially true for residential areas in which urban brownfields or other open spaces are being given up in favour of single-family houses. Almost no multi-storey residential buildings were constructed during the observation period to foster compaction and offer socially acceptable market rents (see Section 4.4).

4.2. Tree-height discrimination

A comparison of tree coverage during the two time periods is valid, albeit with the caveat of the above-mentioned underestimation in 2018. There does not appear to be a significant rate of growth in the more recent time slot (Fig. 5). Nonetheless, it is worth examining the evolution of the urban tree canopy over time. There are no uniform growth rates since different species grow at different rates and are influenced by multiple factors including climate and management practice (Semenzato et al., 2011).

In 2012, an area of 4,441 ha was covered by tree canopies; in 2018 the figure was 5,433 ha (Fig. 4), meaning an increase of 1,000 ha. In 2012, the proportion of young trees below 5 m was 1,100 ha more than in 2018 (Fig. 4). We assume that the major proportion of these trees grew into the mature tree class. The largest change is visible in the 5 to < 7.5 m tree class, where a difference of 374 ha occurs. Between 2010 and 2012, these trees grew to heights of between 5 m and 12.5 m which explains the notable difference in the two figures. It should be taken into account that trees in residential areas, especially in perimeter blocks, are pruned to limit unhindered growth.

Only the proportion of trees in the 12.5–17.49 m class registers an anomaly, with a larger area covered in 2012 than in 2018 (Fig. 7). Since the classification process for 2012 and 2018 is identical, a methodological error is unlikely. It transpires that in 2012, the majority of street trees are between 12.5 m and < 17.5 m high while in 2018 trees in this class occur mainly in the city forest. This is due to forest management activities, including preventative logging and other measures. In future, the Department of Urban Green Areas and Watercourses in the Leipzig City Authority aims to restructure the urban forest to allow it to attain a more natural state with a higher biodiversity (Stadt Leipzig, 2021c).

As urban tree coverage possesses major components of the global carbon cycle, their growth rate and distribution are of great significance.

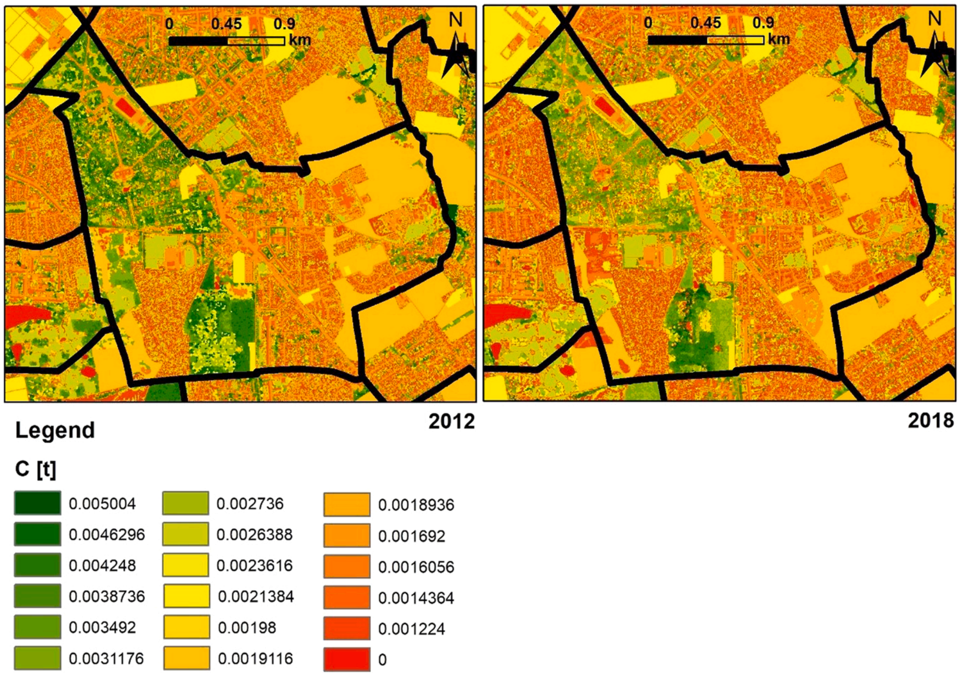


Fig. 8. Very high carbon storage exemplified in the local district Probstheida [t C / pixel].

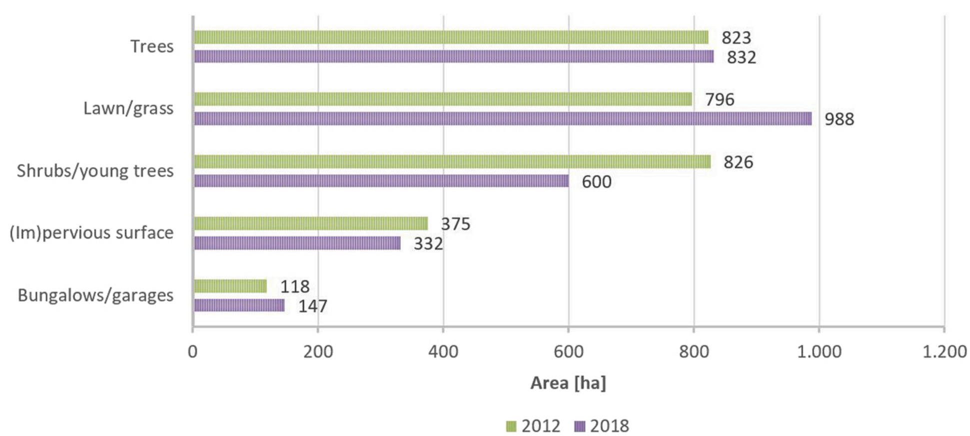


Fig. 9. Land cover change for all local districts within recreation areas.

In their global study, Stephenson et al. (2014) discuss the rate of tree carbon accumulation in dependence to tree size (Stephenson et al., 2014). Although they confirm the general evidence with regard to increasing tree size and age, trees productivity usually declines at the scales of both tree organs (leaves) and tree populations (even-aged forest stands), empirical observations indicate total tree leaf mass increases with growth of tree trunk. Further, they state that increasing individual tree growth rate does not automatically result in increasing stand productivity because tree mortality can drive orders-of-magnitude reductions in population density. That is, even though the large trees in older, even-aged stands may be growing more rapidly, such stands have fewer trees. Tree population dynamics, especially mortality, can thus be a significant contributor to declining productivity at the scale of the forest stand. Regarding the urban woodlands, this observation supports the rejuvenation of the Leipzig alluvial forest to keep productivity high by unevenly aged stands thus securing long-term carbon storage (compare Section 4.3).

Tree coverage varies greatly between the 63 local districts of Leipzig. We include six local districts with significant change in tree cover and illustrate their absolute and relative values in Table 6. The Grünau-Nord district registers an increased tree coverage of more than 15 ha, a gain of over 16% of the total area. It is followed by the districts of Grünau-Mitte and Gohlis-Nord which are all on the outskirts of the city and are chiefly characterised by linear housing. In some areas, the increase in tree coverage is dominated by local woodland planted after the demolition of several linear housing blocks. In 2012, these trees were still classified as young, whereas in 2018 they had reached the height of mature trees. There is a high gain in tree cover in the local districts that are characterised by rental housing with low rents like Grünau-Nord and –Mitte, and Gohlis Nord. Highest loss in tree cover occurs in areas that have few trees anyway, like Zentrum-Süd, Gohlis-Mitte and Gohlis-Süd, though at the low change rate of less than 1%. The latter are characterised by high-priced rents. These findings are in contrast to other studies on the distributive equity of the urban tree canopy cover by Schwarz et al. (2015) as further explained in Section 4.4.

These observations lead to two contrasting results: on the urban planning level, there is an awareness that trees are essential for a variety of ES. Tree planting and maintenance are essential measurements to provide multiple ES in the urban area. However, the tree population is distributed in a very unbalanced manner in the city. Although there is an ecological awareness in the city, the socio-spatial balance of ES through trees is missing (Danford et al., 2014). The latter is an important point in the Leipzig Charter 2020, which target is not attained.

4.3. Carbon storage

This regulating ES indicator describes the amount of carbon stored in the area in 2012 and 2018. The results for all 63 local districts are listed in Table A2. Seven local districts see a decrease in carbon storage, ranging from the minimum of −0.32 t/ha in Lützschena-Stahmeln to the maximum of −6.32 t/ha in Wahren. This decrease can be explained by vegetation loss or change. For instance, in the alluvial forest of the local district of Connewitz, not only the forest management activities are visible in the carbon storage values, but also vegetation stress in the drought year 2018 (Table A2). Hence, the gain in carbon storage comprises a min – max of 0.2–7.26 t/ha value with a gain in the urban forest in Probstheida (Fig. 8). For 2012, an overall carbon storage of 1,656,655 t at 55 t/ha is calculated for the city of Leipzig, which has increased by 2018–1,699,414 t at 57 t/ha. These results are much higher than those calculated by Strohbach and Haase (2012) showing the value of 11 t C/ha for above-ground carbon storage only. Although, this study includes also below-ground carbon pools such a large difference cannot be explained. What supports our study is the research by Richter et al. (2020) who found a carbon storage of 270 t/ha for the city of Berlin, also considering below and above-ground carbon pools. Nonetheless, estimating the totality of carbon storage is still challenging. Further research is necessary to develop tools which are applicable to a city-wide scale.

4.4. Correlation between market rents and green structures

This ES indicator bears a strong relation to socio-economic aspects and is connected to the question of whether economic and environmental conditions are interlinked on a local level and accommodation near green spaces commands higher market rents. Average market rents in Leipzig are typified by high local and temporal variations which is why we decided to analyse them in the context of uGI. With regard to the transfer of our methodology, it must be noted that this data is not publicly available.

During the time period of the study, the average market rent in Leipzig increased by 32% from 5.20 €/m^2 in 2012–6.87 €/m^2 in 2018. While the districts in the city centre register values between 8.90 €/m^2 and 9.38 €/m^2 in 2018, the area of Grünau, which is dominated by linear housing estates, has the lowest average market rent in Leipzig with 5.45 €/m^2.

Table 7 shows that there is an inverted link between the market rent and prevalence of green spaces. The four local districts of Grünau, as well as Mockau-Nord, have relatively low market rents of below 6 €/m^2 and a large average area of green space of between 16 and 19 ha in a 300 m radius. Local districts in the city centre or directly nearby have high market rents and only small areas of green spaces.

Hence the assumption that more green space leads to higher market rents is not proven. This observation differs significantly from research undertaken by Schwarz et al. (2015) that compares several cities across the U.S. and find associated inequities between distribution of urban tree cover and income. Instead, it appears that the proximity to the city centre is the chief explanatory factor for a higher market rent, and the type of built-up structure. Local districts with predominantly perimeter blocks contain few green spaces in their immediate vicinity but higher market rents. Those local districts further from city centre that contain more linear housing accommodate a greater number of residents with lower income, partially in receipt of social welfare, and have lower market rents with plenty of green spaces. As a result, the rental market is not under as much pressure in the outskirts as in or near the city centre. Regarding its evolution, Leipzig does not exhibit a polycentric character. The fact that the rental market in local districts on the fringes of the city is characterised by a relatively small growth of 0.70 € to 1.30 €/m^2 in the average market rent supports this observation.

This study contrasts with other international research in which the value of urban parks is part of the living environment and reflects in higher real estate prices (for both houses and apartments) and family income. Mills et al. (2016) find a positive relationship between urban greenness, social strata, and well-being of urban dwellers. The highest correlation between environmental health based on green infrastructure in neighbourhoods and education is explained in research by Briggs et al. (2008). They find a strong link between the environmental setting in the immediate vicinity and certain components of deprivation, such as a lack of greening of the living environment and environmental health. These measures provide a proxy for resident exposure and allow for a comprehensive analysis of environmental inequity. Our findings are related to the local district level on which we cannot support the results of these international studies at urban area scale. First, it would be useful to have their study broken down to an inner urban differentiated level. Second, we can state from our analysis that high market rents are assigned to certain districts much more than to the green infrastructure in their vicinity.

4.5. Recreation areas

The quantification of the cultural-aesthetic ES indicator shows a wide range in area change between the different local districts. While in 2012, a total of 3,073 ha were assigned to recreation areas, this figure increased to 3,192 ha in 2018. Changes in recreation areas are only permitted in the context of land reallocation via government policy. The district of Dölitz-Dösen's relatively large increase in recreation areas of almost 40 ha is mainly due to the reassignment of a former agricultural exhibition ground (Table A3). With a decrease of 12.6 ha, the district of Großzschocher registers the highest loss of recreation area, followed by Connewitz, Mölkau, Lößnig and Thekla with a decrease of between 4.9 and 8 ha respectively (Table A3). Recreation areas are composed of five predominant land-use classes as listed in Fig. 9. The proportion of mature trees remains almost constant while slight changes occur in the amount of land covered by bungalows and (im)pervious surfaces. The changes in the vegetation class of lawn/grass is caused by a methodological flaw because the dry summer of 2018 registered a decrease in foliage cover during the leaf-bearing seasons and led to a higher mapping result for lawn/grass due to locally varying irrigation measures. The review by the International Federation of Parks and Recreation Administration (IFPRA) reveals the importance of urban green structures beyond parks that include woodland, cemeteries, community and allotment gardens, sports complexes, and other recreational areas (Konijnendijk et al., 2013). In this context, this research intends to raise awareness towards maintaining recreational areas in a well-stratified way. More often, land reallocations are at the expense of open spaces that are to be converted into public infrastructure and residential sites (Cay et al., 2010; Kucukmehmetoglu and Geymen, 2014). For this reason, land reallocation should be handled with care.

4.5.1. Summary of observations

1. In the fast-growing city of Leipzig, urban density is increasing in order to avoid urban sprawl. This densification is not yet being driven by urban consolidation but instead by infill, e.g. into barren land and green spaces. During the study period, a preference was registered for single-family houses while apartment buildings in a linear alignment continued to be demolished.
2. Urban trees play a significant role in fostering sustainable development. Densification processes are not, or not yet, taking place at the expense of urban tree cover and other uGI. Maintenance of the urban forest is evident and rejuvenation is also occurring. The period of drought in 2018 led to a decrease in foliage in deciduous trees and this had dual consequences: on a methodological level, the decrease in leaves meant it was a challenge to compare stands of trees in the two time periods; with regard to climate change, an increasing number of trees will suffer from the predicted increase in very hot

and dry summers and will no longer be able to provide ES to the same extent.

3. Recreation areas can only be changed by government policy and little change is registered overall in this class of land usage. However, it is evident that the distribution of such areas varies across the local districts. In some districts, increases and decreases in recreation areas are significant and this is likely to have an impact on the local population's quality of life.
4. Information on carbon storage helps us to understand the relative changes in the two time periods and the disparities in the urban area. Since the applied model is based on a single value per land cover class, this can provide a valuable estimation for urban areas when detailed information on tree types, etc. is not available. Forest management activities can be clearly observed in the study. The reallocation of land from former commercial to forest areas has an impact on the functional land use and therefore increases the amount of carbon storage in the city.
5. The comparison of market rents reveals a reversal of the expected outcome: residential areas with a relatively high uGI on the urban fringes register lower market rents and rent growth than those districts that lie closer to the city centre and have a comparably lower uGI. Thus, market rents and uGI have become decoupled in the growing city.

5. Conclusions

The defined LULC classes conform to the urban conditions and structures of Central Europe. For regions with different housing structures or less impervious surfaces, the classification process must be modified to fit the respective selection of classes and/or their definitions. Nevertheless, the classification system presented here can easily be applied to other urban areas since the current assignments can be straightforwardly adjusted to the respective situations. A greater amount of open-access input data, however, would facilitate the most successful transfer of this model to other areas. Temporal offsets in the input data can lead to some misclassifications and thus reduce the overall accuracy of the mapping exercise. The overlap in different LULC classes also presented a challenge. This was particularly the case for trees standing in close proximity to buildings which led to the merging of different class objects and flaws in class assignment. It was noted that objects with imprecise boundaries led to different spatial resolutions and therefore hindered high-precision, three-dimensional class assignments and accurate results. In addition, the licence for the software used in the study, eCognition Developer 9.0 by Trimble, is very expensive. Individual users or institutions with a smaller budget may prefer to use open-source software.

The 2020 Leipzig Charter presents concepts for a sustainable and liveable European city. It argues that the provision of well-designed, managed and connected green and blue areas in cities are a prerequisite for achieving healthy living environments, adapting to climate change and preserving and developing biodiversity. This study demonstrates the variations over time in multiple ES in Leipzig and highlighted the disparities in the distribution of ES as well as the accessibility to uGI. Urban trees develop quite differently depending on whether they are in single or contiguous stands and according to the management practices in urban parks and forests. The major classes of built urban structures in residential areas register a wide range in the number and composition of urban green spaces. An unbalanced use of urban space is present, as new inhabitants claim an increase in built-up areas, which again can be detrimental to the provision of uGI and related ES. As we move towards a more sustainable urban development, an equitable amount of uGI must be offered to all residents in a spatially effective and well-balanced way. In order to ensure and maintain the well-being of all residents in a fair way, fast growing cities like Leipzig must make even greater efforts in urban planning.

CRediT authorship contribution statement

Sebastian Elze: Methodology, Software, Data curation, Writing – original draft, Validation, Formal analysis, Investigation, Visualization. **Ellen Banzhaf:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Tables A1,A2,A3.

Table A1
Carbon pool input values for the InVEST model. Zero values are extrapolated by the model.

Land-cover class	Carbon pools			
	Above [t/ha]	Below [t/ha]	Soil [t/ha]	Dead [t/ha]
Unclassified	0	0	0	0
Bungalows/garages	0	0	52.6	0
Shrubs/young trees	34	0	0	0
Lawn/grass	0	0	73.3	0
Linear housing	0	0	39.9	0
(Semi-)detached houses	0	0	39.9	0
High-rise buildings	0	0	39.9	0
Perimeter blocks	0	0	39.9	0
(Im)pervious surfaces	0	0	47	0
Trees 5.0–7.49	34	0	0	0
Trees 7.5–9.99	44.6	0	0	0
Trees 10.0–12.49	55	0	0	0
Trees 12.5–14.99	65.6	0	0	0
Trees 15.0–17.49	76	0	0	0
Treed 17.5–19.99	86.6	0	0	0
Trees 20.0–22.49	97	0	0	0
Trees 22.5–24.99	107.6	0	0	0
Trees 25.0–27.49	118	0	0	0
Trees 27.5–29.99	128.6	0	0	0
Trees 30.0 – 1000	139	0	0	0
Streets	0	0	47	0
Water bodies	0	0	0	0
Agriculture	0	0	53.1	0
Industry and commercial	0	0	59.4	0
Railway structures	0	0	47	0

Table A2
Local districts of Leipzig, Germany, and their respective carbon storage.

Local district	Carbon storage per area in 2012	Carbon storage per area in 2018	Difference in carbon storage
	[t/ha]	[t/ha]	[t/ha]
Probstheida	59.35	66.61	7.26
Anger-Crottendorf	54.50	61.63	7.13
Dölitz-Dösen	62.55	69.22	6.67
Grünau-Ost	55.18	61.71	6.53
Lößnig	53.58	59.70	6.12
Schönefeld-Abtnaundorf	56.91	62.80	5.89
Meusdorf	53.63	59.23	5.60
Marienbrunn	49.01	54.07	5.06
Zentrum-West	51.98	57.03	5.05
Grünau-Siedlung	47.23	52.10	4.88
Lindenau	55.35	60.19	4.84
Gohlis-Mitte	49.31	54.05	4.73
Sellerhausen-Stünz	52.06	56.72	4.66
Gohlis-Süd	51.16	55.63	4.47
Grünau-Nord	50.04	54.22	4.18
Reudnitz-Thonberg	50.95	55.11	4.16
Stötteritz	55.20	59.33	4.14
Südvorstadt	55.39	59.51	4.12
Neustadt-Neuschönefeld	49.84	53.83	3.99
Zentrum-Nord	66.77	70.66	3.89
Volkmarsdorf	50.83	54.71	3.88
Mockau-Süd	53.81	57.48	3.67
Altlindenau	57.65	61.13	3.48
Kleinzschocher	60.77	64.24	3.47
Grünau-Mitte	50.21	53.64	3.42
Zentrum-Südost	54.16	57.43	3.27
Eutritzsch	54.67	57.94	3.26
Mockau-Nord	53.06	56.22	3.16
Großzschocher	46.97	49.80	2.83
Burghausen-Rückmarsdorf	54.11	56.86	2.75
Gohlis-Nord	54.35	56.89	2.54
Neulindenau	54.13	56.63	2.51
Zentrum	48.03	50.49	2.46
Lausen-Grünau	38.19	40.63	2.44
Mölkau	53.58	55.99	2.41
Thekla	53.77	56.16	2.40
Schönau	54.47	56.68	2.21
Möckern	53.77	55.81	2.04
Knautkleeberg-Knauthain	54.93	56.78	1.85
Paunsdorf	54.37	56.01	1.64
Holzhausen	53.29	54.91	1.62
Engelsdorf	51.72	53.31	1.60
Plagwitz	49.94	51.43	1.50
Liebertwolkwitz	54.39	55.84	1.45
Heiterblick	56.70	58.06	1.36
Miltitz	52.76	54.06	1.30
Baalsdorf	52.71	53.92	1.21
Plaußig-Portitz	56.40	57.41	1.02
Zentrum-Süd	50.39	51.28	0.89
Zentrum-Nordwest	16.33	17.19	0.86
Wiederitzsch	52.72	53.51	0.79
Hartmannsdorf	48.13	48.67	0.53
Schönefeld-Ost	55.14	55.62	0.48
Althen-Kleinpösna	46.60	47.02	0.43
Schleußig	68.44	68.71	0.27
Seehausen	53.26	53.46	0.20
Lützschena-Stahmeln	58.45	58.13	-0.32
Böhlitz-Ehrenberg	67.70	65.75	-1.95
Lindenthal	60.48	58.43	-2.05
Leutzsch	75.90	73.62	-2.28
Zentrum-Ost	162.95	160.41	-2.54
Connewitz	85.25	80.89	-4.36
Wahren	81.09	74.77	-6.32

Table A3
Gain and loss in recreation areas between 2012 and 2018.

Local district	Recreation areas 2012 [ha]	Recreation areas 2018 [ha]	Difference [ha]	Local district	Recreation areas 2012 [ha]	Recreation areas 2018 [ha]	Difference [ha]
Dölitz-Dösen	105.9	144.7	38.8	Zentrum-Nord	2.3	2.3	0.0
Seehausen	87.3	106.6	19.3	Heiterblick	0.0	0.0	0.0
Zentrum-Nordwest	178.0	196.9	18.9	Miltitz	26.5	26.4	0.0
Lausen-Grünau	28.0	45.9	17.9	Südvorstadt	40.1	40.0	-0.1
Probstheida	169.6	179.9	10.2	Marienbrunn	25.8	25.7	-0.1
Holzhausen	28.3	36.4	8.1	Gohlis-Süd	38.9	38.6	-0.3
Altlindenau	52.0	59.7	7.7	Althen-Kleinpösna	3.5	3.2	-0.3
Lützschena-Stahmeln	50.4	57.5	7.1	Plagwitz	3.8	3.2	-0.6
Schönau	26.0	32.8	6.7	Stötteritz	89.3	88.7	-0.7
Grünau-Mitte	4.0	9.0	5.0	Schleußig	115.3	114.4	-0.9
Burghausen	50.9	55.3	4.4	Lindenau	24.9	23.8	-1.0
Grünau-Ost	16.1	20.1	3.9	Lindenthal	56.8	55.6	-1.2
Zentrum-Südost	43.2	46.8	3.6	Möckern	104.6	103.3	-1.3
Mockau-Nord	39.1	42.7	3.6	Eutritzsch	75.2	73.7	-1.5
Engelsdorf	52.1	55.5	3.4	Zentrum-Süd	26.4	24.7	-1.7
Zentrum	6.9	9.8	2.9	Gohlis-Mitte	10.2	8.3	-1.9
Liebertwolkwitz	24.5	27.3	2.8	Hartmannsdorf	23.3	21.3	-2.0
Paunsdorf	51.1	53.6	2.5	Sellerhausen	87.4	85.3	-2.2
Grünau-Siedlung	0.1	2.5	2.4	Wahren	34.6	32.4	-2.3
Neulindenau	45.7	47.8	2.1	Meusdorf	22.2	19.9	-2.3
Schönefeld-Ost	25.6	27.5	1.9	Neustadt-Neuschönefeld	10.5	7.9	-2.5
Böhlitz-Ehrenberg	49.5	51.2	1.7	Kleinzschocher	167.0	163.3	-3.7
Leutzsch	69.4	70.8	1.4	Thekla	80.6	75.7	-4.9
Zentrum-West	41.6	42.9	1.3	Lößnig	63.7	58.8	-4.9
Mockau-Süd	47.3	48.3	1.0	Mölkau	42.5	35.7	-6.8
Schönefeld-Abtnaundorf	82.9	83.8	0.9	Connewitz	98.4	90.4	-8.0
Wiederitzsch	20.6	21.3	0.7	Großzschocher	150.1	137.5	-12.6
Knautkleeberg	53.7	54.3	0.6				
Gohlis-Nord	49.9	50.4	0.5				
Anger-Crottendorf	79.1	79.6	0.4				
Plaußig-Portitz	15.5	15.9	0.3				
Reudnitz-Thonberg	24.1	24.4	0.3				
Grünau-Nord	4.1	4.3	0.2				
Volkmarsdorf	16.9	17.0	0.1				
Baalsdorf	9.6	9.7	0.1				
Total [ha]			182.7				-63.78

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