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Mapping urban grey and green structures for liveable cities using a 3D enhanced OBIA approach and vital statistics

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Mapping urban grey and green structures for liveable cities using a 3D enhanced OBIA approach and vital statistics

1. Introduction

1.1 Urban design for liveable cities

Cities are focal points of demographic and economic dynamics. Given that about two-thirds of the world's population will live in cities by 2050 (UN 2015a), the accompanying urban growth patterns will influence urban land use / land cover (uLULC) and the urban form. For decision makers and planners, spatial information such as uLULC and spatially allocated population statistics have become a means of predicting and preparing for future developments at the global, regional and local scale (Banzhaf et al. 2017). The size and morphology of cities have a large impact on the environment in terms of grey and green structures, the provision and distribution of green spaces and even social cohesion (Lauf et al. 2016). How cities and their districts are affected by growth depends greatly on the supply and configuration of housing, adequate social balance and available residential amenities, such as local recreational facilities. To understand the interaction between uLULC and overriding socio-demographic and socio-economic implications of urban populations, the urban structure needs refined mapping on a large scale (Bhatta 2009; De Freitas et al. 2013; Maimaitijiang et al. 2015).

At present, the liveable cities concept views social and environmental sustainability as important aspects (http://liveablecities.org.uk/challenges/future-visions; Southworth 2016; Mesimäki et al. 2017; Onnom et al. 2018). Cities commit themselves to a myriad of initiatives with the overarching goal of maintaining or even improving the quality of life in urban environments by upgrading urban structures and environmental services (Marsal-Llacuna et al. 2015). Using the power and resources available to them, cities undertake great endeavours to improve and adapt environmental, social and economic conditions in an effort to achieve sustainable urban development (Viitanen and Kingston 2014). There is a distinct link between sustainable development and the components used to measure liveability in cities, which indicates there is a relationship between social and economic aspects and environmental sustainability. They can be measured using a combination of indicators relating to each of these components (Kramers et al. 2014; Ahvenniemi et al. 2017). Southworth (2016) points out the complexity of these components, the variation across cities and cultures, and a certain focus on the built environment. He emphasises the form of residential areas, the grey and green structures in the city, and respects the natural setting.

Freely available information and data make it possible to create planning instruments that can (re)act faster along social or economic pathways. De Jong et al. (2015) reflect on these developments and highlight a plethora of new city categories for promoting sustainable urbanisation. Cities are becoming smart in a variety of ways that enable us to monitor, understand, analyse and plan the city, with the aim of enhancing resource efficiency, equity among citizens and quality of life in real time (Batty et al. 2012). Urban liveability and sustainable development therefore focus mainly on intensive engagement in these dimensions, with envisaged targets that can be approached but not yet attained.

To address these complex dimensions, our investigation focuses on the following research questions: (1) How do diverse urban grey and green structures influence residential environments and how can they be steered towards sustainable development in cities? (2) How are different local districts and their residents furnished with grey and green structures? (3) To what extent can an object-based image analysis provide detailed information about urban grey and green structures? (4) What spatially allocated fine scale knowledge can be provided for urban planners and other stakeholders to maintain or even enhance environmental liveability in cities?

Working within a multi-dimensional framework, we aim to use remote sensing techniques to evaluate urban structures in relation to liveability. We will first map urban grey and green structures, such as the allocation and types of green structures in different residential settings, then subsequently contextualise this spatial information using vital statistics at the local level in order to determine indicator values for urban planning instruments. Our main objective is to combine data on grey and green structures with population statistics, so that we can analyse the environmental situation on behalf of residents and determine the supply and potential deficits of urban green spaces at local district level.

1.2 Mapping urban grey and green structures

Urban fabric and socio-spatial structures shape not only neighbourhoods, but also urban districts and thus urban design. Mapping urban composition enhances the visualisation of processes regarding the social, built and natural environment and deepens the understanding of spatial connotation (Rashed et al. 2005). Spatial analysis is a complex process. It relies heavily on the availability of a multitude of information at the same point in time, as well as a consistent spatial scale and planning area. This synergistic approach facilitates interaction between scientists and planners, enabling them to exchange data, knowledge and form a common understanding of what it means to foster sustainable urban development. The latter is the overarching goal (SDG 11, UN 2015b) that ensures urban quality of life.

The natural environment of urban areas has been investigated in various research studies for the purposes of land conservation and ecosystem services (Weber et al. 2006; Derkzen et al. 2015; Grunewald et al. 2017; Endreny et al. 2017). The remote sensing technique is a long-term method that has made it possible to increase the scope of such investigations, especially uLULC, as it refers not only to the green but also to the built elements of a city (Cetin and Levandowski 1991; Ryznar and Wagner 2001; Goetz et al. 2003; Tole 2008; Kane et al. 2014; De Araujo Barbosa et al. 2015). The field of Urban Remote Sensing has witnessed several major advances during the last decade, which has made it feasible to move beyond multispectral pixel image classification. New methods are now available for exploiting very high resolution (VHR) images to evaluate the urban area. There has long been demand for such capabilities, given that the urban area is composed of a very heterogeneous set of features. There is no single set of classifiers that can be used to describe all those spatially and spectrally diverse elements of built and green structures, nor is there a single layer of object delineation to capture these coexisting differentiated features. The most recent urban classification techniques are mainly tailored towards an object-based image analysis – OBIA (Blaschke et al. 2008; Banzhaf and Höfer 2008; O'Neil-Dunne et al. 2014; Puissant et al. 2014; Grippa et al. 2017). In urban areas there is great demand for an accurate geometric differentiation of these structural elements on a fine scale. The incorporation of the third dimension enhances classification accuracy and makes it possible to better identify different features (Yan et al. 2015; Onojeghuo AO and Onojeghuo AR 2017). It is these kinds of scientific and technological innovations

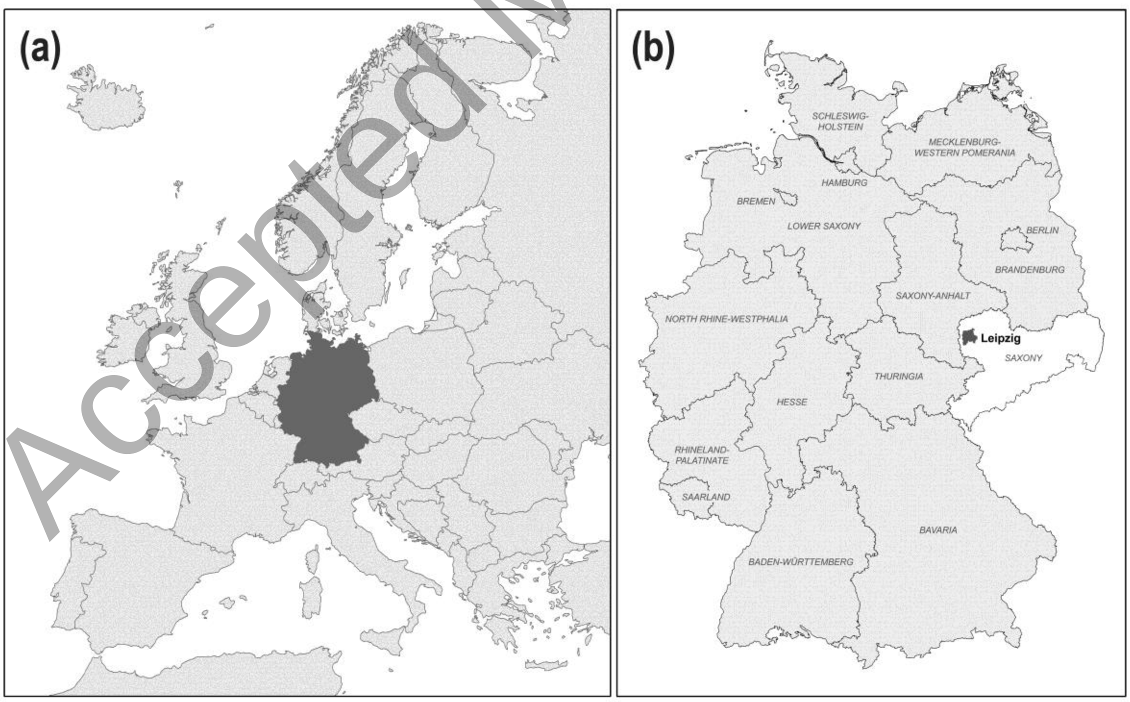
— such as very high-resolution remote sensing systems that deliver spatially explicit data on a large spatial and temporal scale — that support underlying information flows.

This paper follows on from a much smaller study originally presented at the Joint Urban Remote Sensing Event 2017 conference, in the session *Integrated analysis and monitoring approaches for liveable cities* (Wang and Banzhaf 2017).

2. Data and methods

2.1 Study area

At present, one of the fastest growing cities in Germany is Leipzig (Fig. 1), which is located in north-western Saxony. It was part of the former German Democratic Republic, which underwent a severe shrinkage phase after Reunification in 1990. Leipzig is highly dynamic in terms of population development and density (Tab. 1), uLULC and socio-economic disparities. The City Council has made huge efforts to boost its reputation as a modern city and Leipzig is also highly regarded among European cities working towards sustainable urban development (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) 2007).



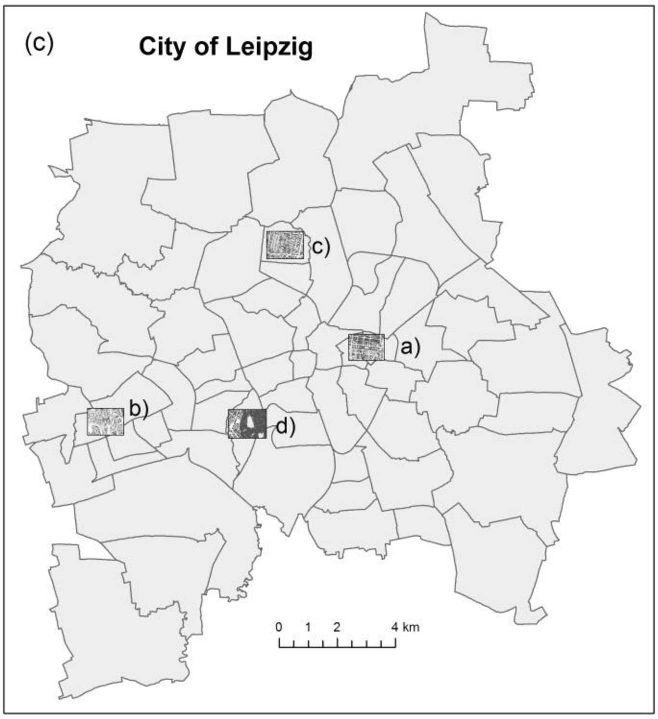


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Figure 1. Location of the case study: (a) Germany in Europe, (b) Leipzig in Germany, (c) Leipzig with its 63 local districts. The four grey and green structure samples a) to d) are described in Section 3 Results.

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Leipzig is located in the Central Lowlands and has one of the most well-preserved floodplain forests in Europe. This alluvial forest extends through the urbanised area from south to north and then towards the northwest, acting as the green lung of the city. In terms of its present housing design, Leipzig has one of the highest proportions of Wilhelminian-style row houses (*Gründerzeithäuser*) in Germany. Construction of these buildings began during the reign of King Wilhelm II in around 1880 and continued until the 1920s. Much later, during the era of the German Democratic Republic, one of the country's largest prefabricated slab building complexes was built in Leipzig. It housed more than 80,000 residents in the 1980s. Another notable phenomenon is the city's high proportion of public community garden allotments (approx. 1,240 hectares) (Stadt Leipzig online [date unknown]), which provide recreational space for thousands of residents and support local climate regulation.

Table 1. Leipzig's demographic and environmental characteristics.

Data source: City of Leipzig, Office of Statistics and Elections (Stadt Leipzig, Amt für Statistik und Wahlen [City of Leipzig, Office of Statistics and Elections] 2017.

Characteristics	**2000**	**2012**	**2017**
Area [km²]	297.54	297.36	297.81
Inhabitants [abs. no.]	479,996	528,540	590,337
Population density [inh./km²]	1,613	1,777	1,982
Forest area in 2012 [km²]	21.0		
Community allotments in 2012 [km²]	12.4		
Latitude	51° 20' N		
Longitude	12° 22' E		
Climate zone	Transitional Continental		
Altitude [m]	113		
Rainfall [mm/a]	595		
Mean temp. [°C]	11.0		

The city's administration is subdivided into 63 local districts, which each have different demands in relation to their built, natural and social environments. Leipzig is undergoing rapid urban growth that is putting great pressure on uLULC. The city authority has therefore taken a dual development approach to inner city planning based on the concept developed by the Federal Institute for Research on Building, Urban Affairs and Spatial Development within the Federal Office for Building and Regional Planning (Gstach and Berding 2016). This concept focuses on the simultaneous densification of both built-up and green areas. Leipzig is consequently a particularly suitable case study for our investigation.

2.2 Characterisation of grey and green structures

When characterising urban structures, their cultural context must also be taken into account. Grey and green structures are pictured in close proximity to one another and shape their urban district or neighbourhood. To deal with the rising rate of land consumption and fragmentation in urban areas, these structures serve as proxies for socio-spatial distinctions (Horwood 2011). The spatially allocated information derived from the analysis of these structures is necessary to plan the physical designs that will foster the various aspects of liveability in cities.

Table 2. Definitions of different classes of grey and green structures.

Class names	Class characteristics	Height above ground [m]
Grey structures		
Bungalow	Single-storey building	2 to < 4
(Semi-)detached house	Multi-storey family house	4 to < 12
Prefabricated slab building and linear housing (since 1960s)	Long lines of linear residential housing with flat roof systems	12 to < 17
Row house (mostly Wilhelminian style 1870-1930)	Closed block development with gable roof	17 to < 24
High-rise building	Multi-storey residential housing	≥ 24
Sealed surface	No vegetation cover, no building	0
Green structures		
Lawn / grass	Homogeneous structural segment	< 0.5
Shrubs / young tree	Heterogeneous vegetation segments	0.5 to < 5
Tree	Heterogeneous vegetation segments	≥ 5

Most grey structures listed in Table 2 characterise typical buildings in Central Europe, which are exemplified by Leipzig. All the grey structures classified as ‘sealed surfaces’ have no elevation above ground, for example roads, parking lots and other paved surfaces. The building definitions require historical characterisation to differentiate between the types of housing, because buildings from a certain era share a similar height, shape and alignment and are often very distinct from buildings from other time periods. The categories described in Table 2 form the foundation for the detailed, rule-based classification of our mapping procedure.

In our study, the urban area has some major building structures that dominate certain districts. Wilhelminian-style row houses are predominant in the central area. They date back to the era of industrialisation in Germany (after 1870 and shortly beyond World War II) and are mainly composed of four-storey houses built in blocks, with gable roofs and interior courtyards. The second prevailing type of housing is made up of prefabricated slab buildings and linearly aligned houses. The first phase of construction was from the 1960s onwards, when such buildings were simply added to existing urban districts, partly as infill developments. The second, more extensive phase took place during the 1980s, when prefabricated slab buildings were built for up to 80,000 residents mainly on the urban fringe.

During the 1920s, community allotments became very fashionable. These large spaces of connected allotments with single bungalows (278 community and other allotment garden areas) characterised Leipzig's urban design. The urban allotments are still an essential feature of the city and serve as a bridge between the built and natural environments. To gain a better picture of the structure of urban vegetation, we have distinguished between trees, scrubs and lawn / grass (Secord and Zakhor 2007). We applied the EEA convention in which trees are defined by a minimum height of five metres (European Environmental Agency (EEA) [date unknown]) (Tab. 2). The Conservation Fund (2004) defined green infrastructure as an interconnected network of natural and semi-natural features, areas and green spaces that support native species, maintain natural ecological processes in rural and urban areas, and contribute to the health and quality of life of human beings. Later on, the definition was extended to include parks, forest reserves, terrestrial freshwater, coastal and marine areas, as well as man-made elements such as ecoducts and cycling paths (European Commission 2013).

2.3 Mapping grey and green structures with OBIA

2.3.1 Data preparation

The remotely sensed part of this study is based on digital orthophotos (DOP) taken in 2012. The images are multispectral and consist of the red, green and blue wavelengths of the visible spectrum and the near-infrared band. This data was acquired and processed by the Ordnance Survey of the State of Saxony (2012). All DOPs possess a ground resolution of 20 cm and are stored in the form of 2 km x 2 km tiles. In addition, LiDAR derivatives facilitate altitude information and are used to differentiate various building and vegetation structures according to their height. The digital elevation model (DEM) is derived from laser scanner measurement techniques. Primary data is georeferenced and subdivided into first-echo-points, last-echo-points and only-echo-points. These points are interpolated by the Ordnance Survey (2012) and the results are publically available. Height precision (z direction) of all mesh points in the DEM is +/- 0.2 m with a significance threshold of 95% for mesh sizes of 2 m x 2 m (x, y directions). The digital surface model (DSM) describes the surface of vegetation, built-up areas and open spaces using three-dimensional coordinates of the first-echo-points and only-echo-points measured by laser scanner technology. The precision is similar to that of the DEM.

During the pre-processing stage, DOPs, DEMs and DSMs are mosaicked to cover the whole of Leipzig. The pixel size of the DOPs needed to be resampled to 60 cm due to data processing limitations. In this context, the resampling of DOPs is ideal for distinguishing various grey and green structures and filtering out extreme heterogeneities (e.g. roof windows) inside objects that need to be delineated later on (Chen et al. 2012). DEMs and DSMs are resampled to 60 cm as well, to ensure the pixels are the same size and the data can be merged. While preserving the edges, local noise reduction is achieved by applying a multi-direction Lee filter to the raster data sets (Lee 1981).

To support object differentiation and determine the attributes of the target objects, derivatives of the initial input data were created prior to the segmentation and classification procedure. We generated a normalised digital surface model (nDSM) that represents the true object height by subtracting the DEM from the DSM. Furthermore, the red and near-infrared bands of the orthoimagery were used to calculate the normalised difference vegetation index (NDVI). Ancillary vector data of building footprints and industrial areas were provided by the city authorities. All input data sets were assigned to the same georeference system: ETRS89/UTM Zone 33N (EPSG:25833).

2.3.2 OBIA mapping process

The quality of the object delineation is vital for ensuring the accuracy of the classifications, so we processed the data using an incremental, hierarchical approach. For the initial segmentation of the image layers, we used eCognition Developer 9.0.0 software (Trimble Geospatial, Munich, Germany) to apply quadtree segmentation, with the aim of delineating and characterising homogeneous urban grey and green objects. We chose this specific multi-resolution segmentation approach to delineate the objects, because our experience in a previous study proved very positive (Banzhaf and Kollai

2015) and it delivered a good balance between efficiency and quality. In the object-based image analysis (OBIA), the features were characterised using spatial, spectral and morphological metrics. Using the red, green, blue and near-infrared bands of the DOP, the image domain is split up according to the homogeneity of the respective spectra of objects. We set the scale parameter to 40 and incorporated the building footprints vector layer to generate well-positioned building objects with true outlines. Industrial buildings were masked using vector information, as this study focuses on residential areas.

The preliminary subdivision of uLULC into vegetated and sealed surfaces was based on the objects' NDVI values, with a threshold of 0.09. Minor corrections of the boundaries of built objects were performed using the grow region algorithm. The detailed classification of grey and green structure types was facilitated by the use of different height variables, e.g. mean and quartiles of object height (Rutzinger et al. 2007). Including these statistical measures makes it possible to reduce the degree of error resulting from the offset of DOP and nDSM, which is caused by the central camera perspective and different acquisition technologies. The rule-based classification was carried out according to the characteristics of grey and green structures detailed in Section 2.2. To further refine the edges of tree objects, we subdivided the tree class by applying contrast split segmentation. By taking into consideration edge contrasts of height information, it was possible to produce tree objects with a more realistic shape. As a consequence, some boundary objects were reclassified and assigned to adjacent vegetation classes where appropriate.

The classification scheme is organised into several hierarchical levels, with basic land cover classes at the first level and refined uLULC classes at the subsequent levels. The classification was carried out using rule-based classifiers as described in Table 3.

Table 3. A segmentation scheme is a crucial prerequisite in OBIA.

Level 1	Level 2	Level 3	Abbreviation
Binary land cover	Refined uLULC	Subdivisions of uLULC	uLULC
Vegetated	Lawn/grass	Lawn/grass	LG
	Shrubs/young tree	Shrubs/young tree	ST
	Tree	Tree	TR
(Non-) vegetated surfaces	Sealed surface	Sealed surface	SS
	Bungalows	Bungalows	BU
	Buildings	(Semi-)detached house	SD
		Prefabricated slab building and linear housing	PS
		Row house (mostly Wilhelminian style)	RH
		High-rise building	HR
Unclassified	Unclassified	Unclassified	UC

2.4 Combined analysis of grey and green structures with vital statistics

Today's cities face challenges such as crowding, climate adaptation, air pollution and a heterogeneous population structure exposed to environmental burdens. To foster liveability, cities need to integrate data sets into their knowledge platform. Stakeholders could thus benefit from precise assignment based on remotely sensed data to make well-allocated decisions for creating value in city neighbourhoods. Compared to the very high spatial resolution of remote sensing data, the spatial resolution of data from vital statistics is relatively low. Population data is gathered according to different administrative divisions, i.e. entire city, local districts, statistical units and so on. Therefore the statistical data appears to be evenly distributed within those divisions. Population representation always varies according to the spatial assignment. Given that modifiable area units may lead to problems (MAUP phenomenon), we analysed all datasets on the same level.

In terms of vital statistics, socio-economic data is not readily available in Germany. If we assume that housing reflects social strata, one could suggest that residents in linear housing are likely to have lower income levels, whereas residents in single family houses, i.e. (semi)detached houses, would belong to the middle class. A wider array was assigned to the Wilhelminian-style row houses, where all social strata can be found.

Vital statistics are used to link grey and green structures with selected population indicators. At regular intervals, official statistics are gathered by the City of Leipzig and the Office of Statistics and Elections (Stadt Leipzig, Amt für Statistik und Wahlen [City of Leipzig, Office of Statistics and Elections] 2012, 2013a, 2013b, 2014). To match the available geodata set, we chose to use statistics from the year 2012 for our socio-spatial analysis. All quantified data was allocated to the above-mentioned 63 local districts and shared with researchers based on a mutual contract. The city authorities are in favour of exchanging data and knowledge with scientific institutions as a way of fostering the development of a smarter city.

2.4.1 Spatial scale for integrated urban planning

The analysed data was quantified for the entire city and the respective outcomes were subdivided into the more refined and meaningful level of administrative units. Therefore, our sample size comprises 63 local districts. The districts are a relevant planning level for different city authorities and most vital statistics are freely available at the local district level. To identify the rather critical uLULC types connected with residential exposure for each unit, we first ranked the socio-demographic features — especially those characterising the urban population — and then extracted the upper quartile (i.e. > 75%) of our sampled data for each local district. This enabled us to investigate the more challenging local districts with regard to the connection between socio-demographic and health-related indicators, as well as grey and green structural elements.

3. Results

3.1 Mapping of grey and green structures by remotely sensed data

Using the above-mentioned OBIA approach, we mapped the mosaicked imagery of the entire city on several segmentation levels. The integrated spatial and spectral information was processed in accordance with the detailed class descriptions to achieve high differentiation. The location of the displayed samples is shown in Fig. 1c, while sampled urban structures are presented in Fig. 2 a-d.

Typically, grey structures of row houses belong to the central part and prefabricated slab buildings tend to be located in the suburban area. The samples given in Fig. 2 a-d explain the classified grey and green structures in the city of Leipzig for the year 2012. We characterised a new class of building, as there are several newly constructed houses scattered in between the other buildings that neither belong to the row nor to family house categories due to their mixed height information. They form a major part of the unclassified category.

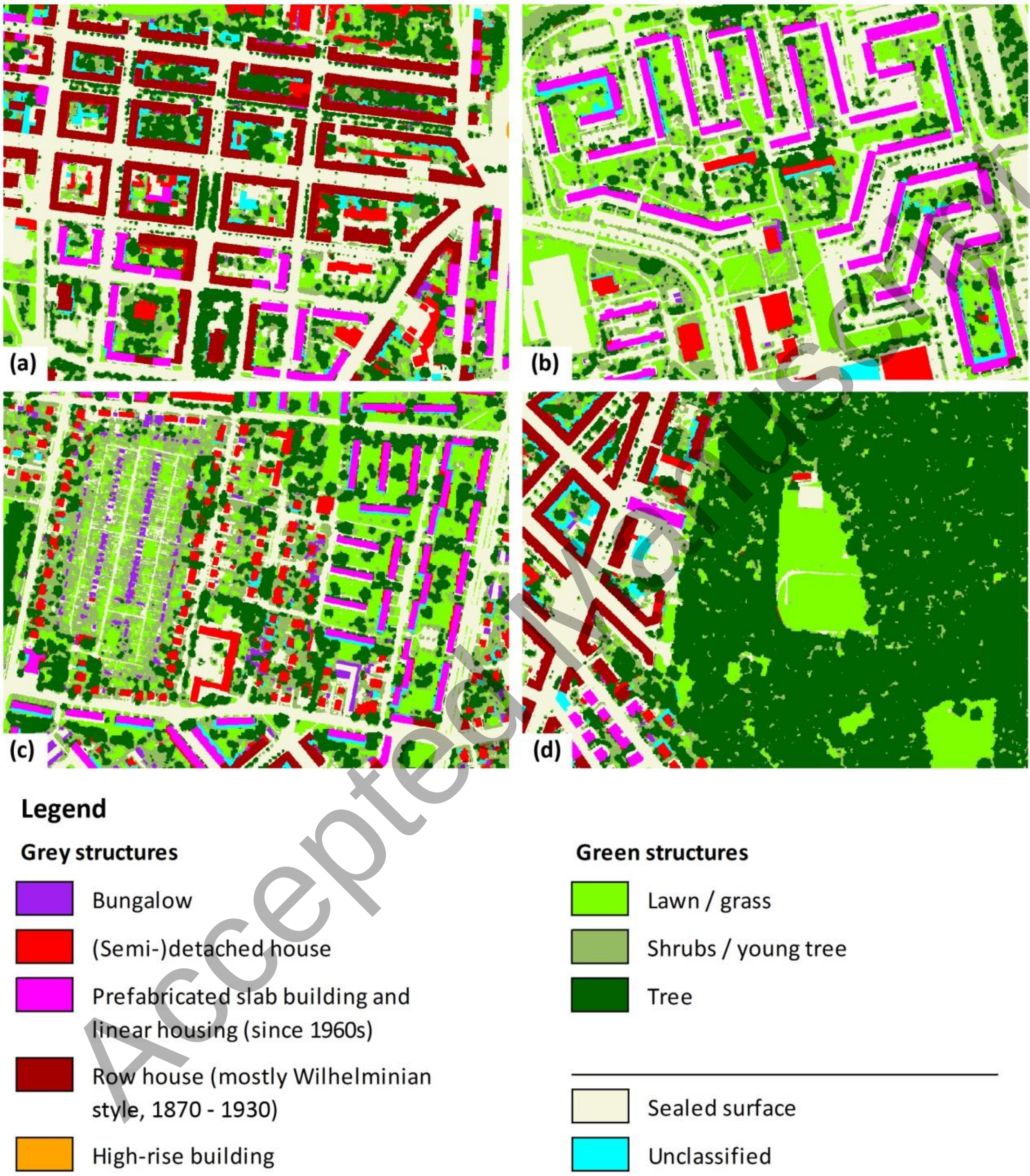

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Figure 2. Types of grey and green structures.

(a) Wilhelminian-style row houses in block developments with interior green spaces (central and northern part); accompanied by linear housing (southern part).

(b) Prefabricated slab buildings with large areas of lawn / grass.

(c) (Semi-)detached houses in the west and centre, large community allotments with bungalows in the west; linear housing in the eastern and southern parts.

(d) Urban alluvial forest with large meadow in the central part; adjacent Wilhelminian-style row houses in the western part.

3.2 Accuracy assessment

To understand the quality of our analysis, we examined the thematic output using an equalised random accuracy assessment procedure. This type of accuracy assessment offers the advantage of an equally distributed sample size across all the classified objects, giving each class the same amount of control points, regardless of the predominance of any class type in the study area. We sampled 100 points per class, assigned them according to several reference data such as DOPs, Google Maps and expert knowledge, then assessed the overall accuracy as well as user's and producer's accuracy and the Kappa metrics (Tab. 4). The detailed confusion matrix supports the quality of OBIA by expressing the assignment of all 1,000 points to the respective classes. The Kappa coefficient reflects the difference between actual agreement and the agreement that would result from a random experiment. It demonstrated the best results for lawn and grass, sealed surface and trees. We achieved the highest producer's accuracy for shrubs and young trees. The user's accuracy values were highest for lawn and grass, followed by high-rise buildings, sealed surface and trees.

Table 4. Accuracy assessment of grey and green structures.

	UC	SS	LG	ST	TR	BU	SD	PS	RH	HR	Producer´s accuracy [%]	User´s accuracy [%]	κ
UC - Unclassified	36	28	1	-	1	13	7	-	6	-	-	-	0.35
SS - Sealed surface	3	107	1	-	-	2	-	-	-	-	71.8	94.7	0.94
LG - Lawn / grass	-	1	100	-	-	-	-	-	-	-	84.0	99.0	0.99
ST - Shrubs / young tree	-	-	11	80	13	2	-	-	-	-	98.8	75.5	0.73
TR - Tree	1	-	6	-	98	-	2	-	-	-	87.5	91.6	0.91
BU - Bungalow	2	10	-	1	-	76	2	-	-	-	72.4	83.5	0.82
SD - (Semi-)detached house	7	1	-	-	-	12	73	4	2	-	85.9	73.7	0.71
PS - Prefabricated slab building and linear housing (since 1960s)	6	-	-	-	-	-	1	51	38	-	86.4	53.1	0.50
RH - Row house (mostly Wilhelminian-style, 1870-1930)	8	1	-	-	-	-	-	4	85	-	64.4	86.7	0.85
HR - High-rise building	2	1	-	-	-	-	-	-	1	93	100.0	95.9	0.95
											Overall		
											Classification accuracy 79.80		Kappa statistics 0.78

The overall classification accuracy is only an initial and average value. It does not explain the individual class assignments or precisely show the strengths and weaknesses of the quantification. Detailed analysis of the confusion matrix and the producer's and user's accuracy allowed us to conclude that the green structures could be assigned with a very high degree of accuracy. Some errors may occur in the confusion between young trees (below 5 m) and mature trees (5 m and above) due to the mesh width of the DSM. The differentiation between grey structures seems to be more challenging. Some height information may overlap between the two types of buildings: prefabricated slab buildings and row houses. There are two possible reasons for an incorrect assignment: (1) if a sample of these two types is distinctly higher or lower than their average class member, or (2) if Wilhelminian-style row houses were recently reconstructed without their typical gable roof. Therefore, the main confusion occurs with prefabricated slab buildings. In this case, the expert knowledge is used to make a distinction between these two grey structural features based on whether they are located in the central or suburban parts of the city.

3.3 Urban structural and socio-demographic indicators

To depict the ranges of grey and green structures linked to vital statistics in the city, the minimum and maximum values are presented in Table 5. This overview visualises the wide range of values in absolute (e.g. inhabitants) and relative (grey and green structures) figures, as well as their share (grey and green structures per inhabitant). The population density varies tremendously, as does the provision of green structures per inhabitant. Lower and upper quartiles were calculated for all local districts.

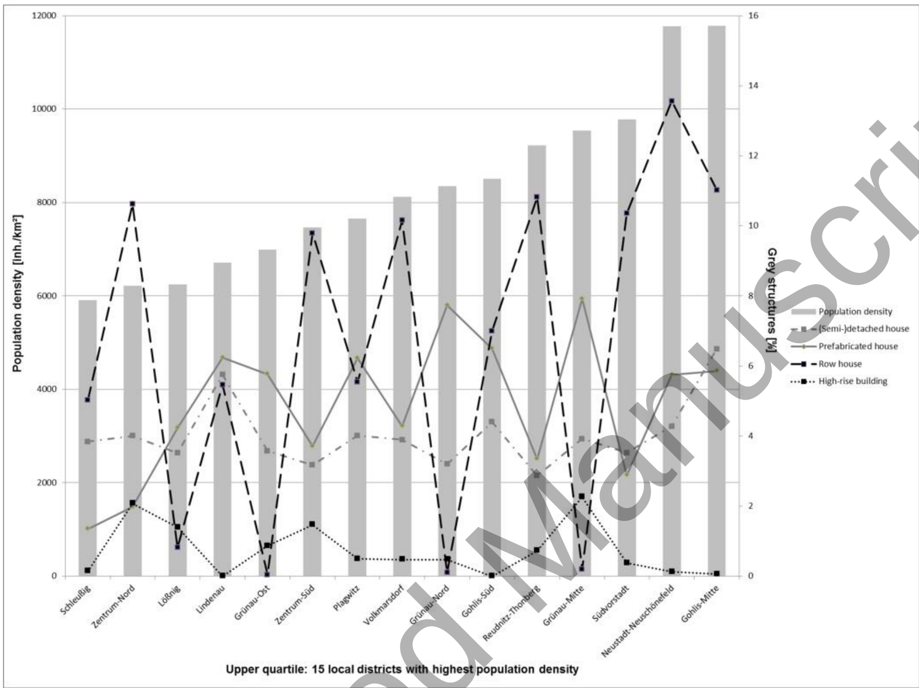
Table 5. Overview of statistics for selected indicators across all local districts in Leipzig.

Indicators	**Minimum**	**Maximum**
Grey structures		
Residential built-up area [%]	0.86	34.25
Residential built-up area per inh. [m²/inh.]	13.77	161.82
(Semi-)detached houses [%]	0.85	9.34
Prefabricated slab buildings [%]	0.01	7.91
Row houses [%]	0.00	16.32
High-rise buildings [%]	0.00	14.13
Green structures		
Green structures in total [%}	16.65	78.23
Trees [%]	2.61	61.60
Green structures per inh. [m²/inh.]	32.61	5,905.34
Population		
Inhabitants [abs. no.]	1,308	23,570
Population density [inh./km²]	83	11,781
Human health indicator		
Share of obese inhabitants [%]	3.4	21.8

To assess particular indicators of the vital statistics, the upper quartile was extracted, i.e. the quarter of the local districts with the highest values (Fig. 3 to 5). When this was overlaid with the grey and green structures, it was possible to clearly see which local district(s) have abundance or lack of green structures and which grey structures are dominant in areas with a supply / absence of ecosystem services (compare Hansen and Pauleit 2014).

Population density is a major driver of urban land-use pressure. This raises the question: which housing types are predominant in areas with high population density? Could we expect there to be no (semi-)detached houses in the upper quartile in terms of population density? And should we assume that high-rise buildings are responsible for such a dense settlement structure?

Fig. 3 explains where residents live in the upper quartile of population density. Astonishingly, some of those upper quartile residents do live in (semi-)detached houses and that type of housing makes up about 3% to 6% of the grey built-up structure. Even more striking was the fact that high-rise buildings with a maximum of only 2% do not explain the high population density in this sample. We found two dominant categories of building types in this quartile with extreme ranges: prefabricated slab buildings and linear housing (2% to 8%), which are almost inversely proportional to the predominant type Wilhelminian-style row houses (0% to almost 14%). It is this historical building type that accounts for the highest density of residential living space in the city.



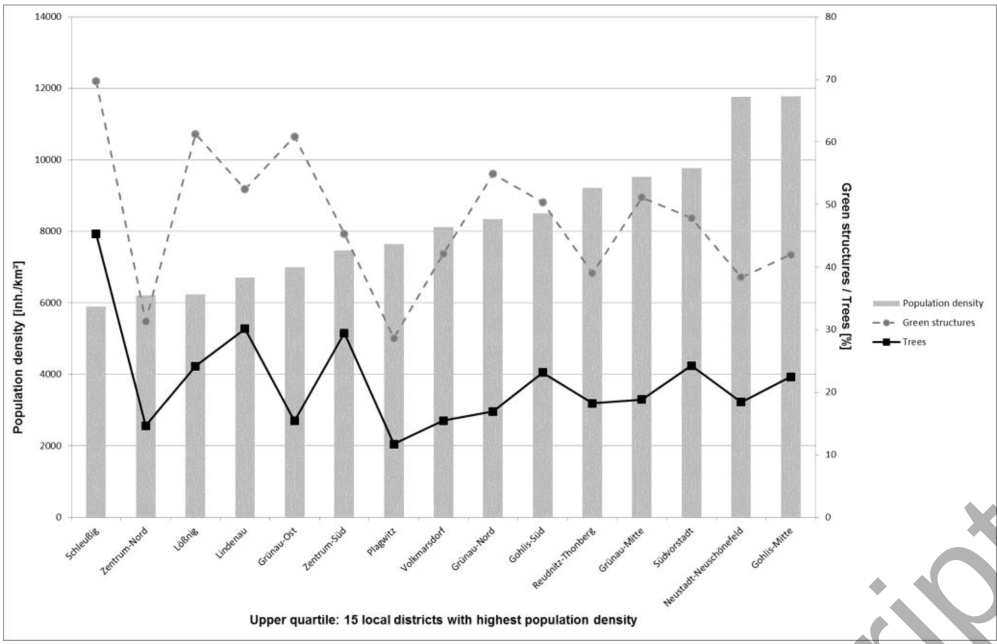
##################### place figure 3 here #####################

Figure 3. Population density mirrored on the different grey structures. The graphic depicts the upper quartile, i.e. the 15 most densely populated local districts of Leipzig.

###########In black and white for paper publication###########

###########In colour for online publication##############

Another focal point addresses the question of whether residents who live closely together in local districts have a density of grey structures in their neighbourhood, or if green structures are equally available in that very area for regulating, provisioning and cultural ecosystem services.



#################### place figure 4 here ####################

Figure 4. Population density mirrored on green structures in general and trees in particular. The graphic depicts the upper quartile, i.e. the 15 most densely populated local districts of Leipzig.

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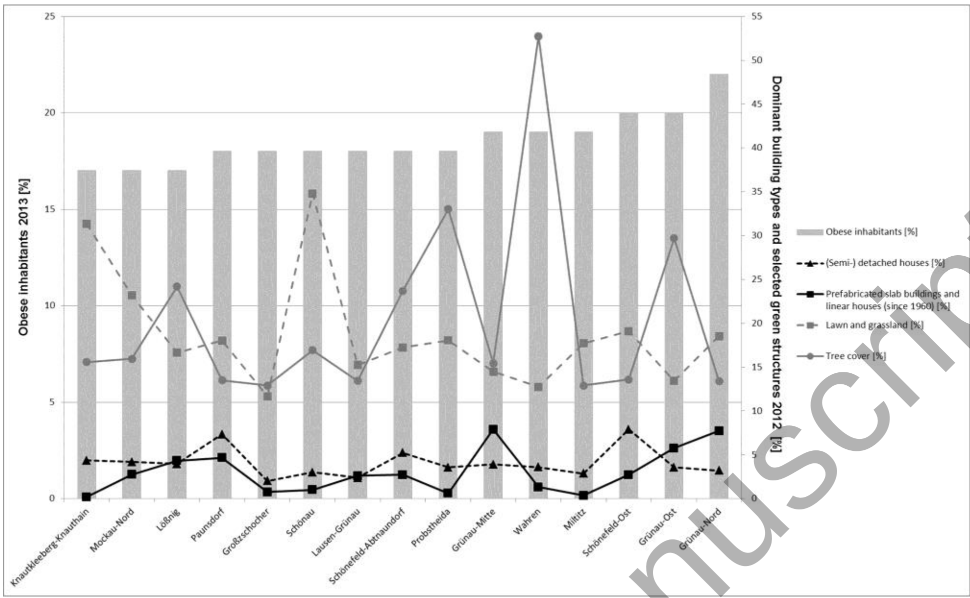
############In colour for online publication##############

The population density in the upper quartile ranges from almost 6,000 to nearly 12,000 inh./km², while the share of green structures varies between 30% and 70%, decreasing at an inversely proportional rate (Fig. 4). Still, green structures are available to cover recreational needs to some extent, whereas the provision with trees only has a share of about 10% to 45%. The green structures are unequally distributed in the districts with the highest population density at the cost of least furnishing and low tree cover for the provision of cooling effects and air purification.

A further aspect of city planning is to provide incentives for physical activities, especially among obese inhabitants. In the context of human health, we investigated where most of the obese population is located and the extent to which their surroundings are furnished with green infrastructure. According to the World Health Organisation (WHO 2000), people with a body mass index ≥ 30 are considered obese. As an indicator, obesity refers to health aspects and consequently cannot be determined by spatial structures of the urban fabric. Liveable cities aim to create healthy environments and reach out to citizens in order to reduce and/or prevent diseases such as obesity. Ensuring walkability in residential areas is one of the many health promotion strategies available to urban planners. Hence, we analysed the dominant building types and selected green structures in the 15 local districts with the most obese populations (Fig. 5).



################### place figure 5 here ########################

Figure 5. Obese inhabitants mirrored on the dominant building types and selected green structures. The graphic depicts the upper quartile, i.e. the 15 local districts of Leipzig with the highest share of obese inhabitants. The obesity figures were provided by the City of Leipzig, Office of Statistics and Elections (2013c).

###########In black and white for paper publication############

############In colour for online publication###############

The results displayed in Fig. 5 were significant for us, dissenting clear statements about the strong correlation between lower social status and obesity in the relevant literature. In a study by Apouey (2016) the socioeconomic status was associated with a higher family income and less body fat for children. A similar connection between low family income and a prevalence of excessive body weight among children is discussed by Lynch et al. (2016). In our study, the results do not indicate a simple correlation between socioeconomic strata and obesity. The highest numbers of obese inhabitants are found in districts in which the dominant housing types are prefabricated slab buildings as well as (semi-)detached houses. According to this result, obesity is not merely a social problem. Instead, it affects different social strata of our affluent society. In the local districts in question, relevant green structures for physical activities were extracted: the share of lawn and grassland ranged from 11% to 35% and the share of trees was between 12% and 53%. Generally speaking, inhabitants can perform their daily recreational activities in their respective neighbourhoods on lawns and grassland and they can profit from the ecological benefits of trees, such as shade and cooling. With information on grey and green structures, urban planners can establish spatially explicit incentives for appropriate physical outdoor activities to improve the health of citizens affected by obesity.

4. Discussion

When reflecting on urban planning for liveable and resilient cities, grey and green structures should be analysed and understood collectively. The strength of our study is that we have mapped an entire city on a fine spatial scale, which offers tremendous opportunities to analyse a variety of indicators that relate to the Green Infrastructure concept. Moreover, we quantified the grey structure of a typical Central European city and could thereby visualise the distribution of urban structure types. By spatially assigning population statistics to administrative units, such as the city's local districts, we gained insights into the residential structure and could link those statistics with the urban structure types to detect inequalities in the urban setting.

In the field of publicly available data, it is a limitation that socioeconomic data in countries like Germany are not easily available. Socioeconomic information should be incorporated into spatially explicit analyses, so that the urban structure can be enhanced to address socio-environmental inequalities. In this respect, the urban grey and green structure types deliver an initial approach for explaining the social strata from a spatial perspective and fill that gap. It is the overlay of the spatial information on uLULC and population data that reveals spatially allocated vegetation deficits facing residents in specific local districts.

Availability of local, national and global point cloud data could push forward mapping and modelling of urban areas and related environmental impacts by incorporating the third dimension into all spatial analysis. That would lead to a more realistic picture of the urban areas. Further refinements could be undertaken in the methodological section, which underlines the need for a better quality of input data.

LiDAR/ ALS point clouds would provide more precise object height information, could enhance the OBIA approach and help to increase the classification accuracy. Another aspect for further studies is to examine the performance of other classifiers. In contrast to a rule-based classification, machine-learning classifiers could be used to integrate a broader set of spectral, textural and geometric variables derived from the objects to rank the contributing variables.

A certain limitation is given to researchers in terms of transdisciplinary studies and the close collaboration with stakeholders. When talking about urban policy and planning relevance, researchers must consider finding ways to have their results incorporated into urban authority planning decisions. The most challenging of research is trying to get research findings implemented. We need to translate our results in order to be understood by planners. It is very important finding a common language to encourage a willingness to learn from each other and incorporate aspects from science into practice and vice versa.

5. Conclusion and outlook

Our analytical approach facilitates a broad view of urban areas as interrelated socio-ecological and spatially explicit land use systems. On different levels, urban development seeks to increase or to maintain the quality of life in urban areas by implementing improvements that focus on humans and the environment. For instance, by ensuring fair and well-distributed ecosystem services, it is possible to develop renewable concepts for a city's neighbourhoods or even whole regions. This study successfully implemented combined data exploitation at the appropriate scale of local districts, thereby confirming the feasibility of this approach. The examination of the performance of spatial indicators may allow further inner urban differentiations and greater focus on the neighbourhood level within local districts. However it would be necessary to acquire the corresponding vital statistics, which would be very expensive. For some large German cities, vital statistics may exist for finer spatial units such as block levels, but they are not freely available. As such, this study may serve as a way of selecting subareas for further in-depth analysis.

This integrated mapping approach is necessary for the identification of options for further innovative urban green structures, such as green façades and roofs, especially in districts with a high share of grey structures. Therefore, the integration of socio-demographic and health-related statistics provides a valuable knowledge framework in dynamic urban settings. The combined analysis of mapped OBIA land-use categories and sophisticated evaluation of vital statistics creates added value. It fosters knowledge regarding where and how to develop cities in order to achieve healthier and fairer urban living.

Strong collaborations between researchers and planners are critical for achieving the goal of sustainable and liveable cities. Innovative solutions for resource-efficient, climate-adapted and healthy cities depend on a smart network of different planning authorities, stakeholders and researchers, as well as economic and health experts. In turn, they rely on well-analysed spatial data and in-depth information about allocated socio-demographic indicators on a fine scale. Shared knowledge is the key to joint initiatives for the implementation of smart environmental solutions for sustainable urban development and an adequate quality of life in cities.

References

Ahvenniemi H, Huovila A, Pinot-Seppä I, Airaksinen M. 2017. What are the differences between sustainable and smart cities? Cities 60: 234–245.

Apouey BH. 2016. Child physical development in the UK: the imprint of time and socioeconomic status. Public Health 141:255-263.

Baatz M, Schäpe A. 2000. Multiresolution Segmentation – an optimization approach for high quality multi-scale image segmentation. In: Strobl J et al. editors. Angewandte Geographische Informationsverarbeitung XII. Heidelberg, Germany: Wichmann; p. 12–23.

Banzhaf E, Kabisch S, Knapp S, Rink D, Wolff M, Kindler A. 2017. Integrated research on land-use changes in the face of urban transformations – An analytic framework for further studies. Land Use Policy 60:403–407.

Banzhaf E, Höfer R. 2008. Monitoring urban structure types as spatial indicators with CIR aerial photographs for a more effective urban environmental management. Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS), IEEE. 1(2):129–138.

Banzhaf E, Kollai H. 2015. Monitoring the Urban Tree Cover for Urban Ecosystem Services-The Case of Leipzig, Germany. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-7-W3. [accessed 2018 January 12]:[5 p.]. https://doi.org/10.5194/isprsarchives-XL-7-W3-301-2015.

Batty M, Axhausen KW, Giannotti F, Pozdnoukhov A, Bazzani A, Wachowicz M, Ouzounis G, Portugali Y. 2012. Smart cities of the future. The European Physical Journal. Special topics 214: 481–518.

Bhatta B. 2009. Analysis of urban growth pattern using remote sensing and GIS: a case study of Kolkata, India. Int. J. Remote Sens. 30:4733–4746.

Blaschke T, Lang S, Hay G, editors. 2008. Object-based image analysis: spatial concepts for knowledge-driven remote sensing applications. Berlin Heidelberg: Springer.

[BMUB] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, editor. 2007. Leipzig Charta für nachhaltige europäische Städte. Berlin: BMUB.

[BMUB] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, editor. 2007. Leipzig Charter on Sustainable European Cities. Berlin: BMUB. German.

Cetin H, Levandowski W. 1991. Interactive classification and mapping of multi-dimensional remotely sensed data using n-dimensional probability density functions (nPDF). Photogrammetic Engineering & Remote Sensing. 57(12):1579–1587.

Chen LC, Huang CY, Teo TA. 2012. Multi-type change detection of building models by integrating spatial and spectral information. International Journal of Remote Sensing. 33(6):1655–1681.

The Conservation Fund. 2004. Green Infrastructure. [accessed 2017 July 05]. https://www.conservationfund.org/our-work/strategic-conservation-planning.

De Araujo Barbosa CC, Atkinson PM, Dearing JA. 2015. Remote sensing of ecosystem services: A systematic review. Ecological Indicators. 52:430–443.

De Freitas MWD, Dos Santos JR, Alves DS. 2013. Land use and land cover change processes in the Upper Uruguay Basin: linking environmental and socioeconomic variables. Landsc. Ecol. 28:311–327.

De Jong WM, Joss S, Schraven D, Weijnen M. 2015. Sustainable-smart-resilient-low carbon-eco-knowledge cities: making sense of a multitude of concepts promoting sustainable urbanization. Journal of Cleaner Production. 109:25–38.

Derkzen ML, Teeffelen AJ, Verburg PH. 2015. Quantifying urban ecosystem services based on high-resolution data of urban green space: an assessment for Rotterdam, the Netherlands. J. Appl. Ecol. 52(4):1020–1032.

Endreny TA, Santagata R, Perna A, Ulgiati S. 2017. Implementing and managing urban forests: A much needed conservation strategy to increase ecosystem services and urban wellbeing. Ecological Modelling. 360:328–335.

[EEA] European Environmental Agency. EUNIS categories. Habitat Types Key Navigation. Category: (G) Woodland, forest and other wooded land. [accessed 2018 January 12]. http://eunis.eea.europa.eu/habitats-key.jsp?level=2&idQuestionLink=--%3E&pageCode=G.

European Commission. 2013. Building a Green Infrastructure for Europe. Luxembourg: Publications Office of the European Union. [accessed 2017 July 05]:[24 p.]. http://ec.europa.eu/environment/nature/ecosystems/docs/green_infrastructure_broc.pdf

Goetz SJ, Wright RK, Smith AJ, Zinecker E, Schaub E. 2003. IKONOS imagery for resource management: Tree cover, impervious surfaces, and riparian buffer analyses in the mid-Atlantic region. Remote Sensing of Environment. 88:195–208.

Grippa T, Lennert M, Beaumont B, Vanhuysse S, Stephenne N, Wolff E. 2017. An Open-Source Semi-Automated Processing Chain for Urban Object-Based Classification. Remote Sens. 9(358). [accessed 2018 January 31]:[22 p.]. http://www.mdpi.com/2072-4292/9/4/358.

Grunewald K, Richter B, Meinel G, Herold H, Syrbe R-U. 2017. Proposal of indicators regarding the provision and accessibility of green spaces for assessing the ecosystem service “recreation in the city” in Germany. International Journal of Biodiversity Science, Ecosystem Services & Management. 13(2):26–39.

Gstach D and Berding U. 2016. [Dual development of inner city planning - rediscovering a former principle under difficult conditions]. Informationen zur Raumentwicklung. 6:661-673.

Hansen R, Pauleit S. 2014. From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. Ambio. 43:516–529.

Hese S, Behrendt F. 2017. Multiseasonal tree crown structure mapping with point clouds from OTS quadrocopter systems. ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XLII-2/W6:141–143.

Horwood K. 2011. Green infrastructure: reconciling urban green space and regional economic development: lessons learnt from experience in England's north-west region. Local Environment. 16(10):963–975.

Kane K, Connors JP, Galletti CS. 2014. Beyond fragmentation at the fringe: A path-dependent, high-resolution analysis of urban land cover in Phoenix, Arizona. Applied Geography. 52:123–134.

Kramers A, Höjers M, Lövehagen N, Wangel J. 2014. Smart sustainable cities-exploring ICT solutions for reduced energy use in cities. Environmental Modelling & Software. 56:52–62.

Lauf S, Haase D, Kleinschmit B. 2016. The effects of growth, shrinkage, population aging and preference shifts on urban development – A spatial scenario analysis of Berlin, Germany. Land Use Policy. 52:240–254.

Lebourgeois V, Dupuy S, Vintrou E, Ameline M, Butler S, Bégué A. 2017. A combined random forest and OBIA classification scheme for mapping smallholder agriculture at different nomenclature levels using multisource data (simulated sentinel-2 time series, VHRS and DEM). Remote Sensing. 9(3):e259.

Lee JS. 1981. Speckle analysis and smoothing of synthetic aperture radar images. Computer graphics and image processing. 17(1):24–32.

Lynch BA, Agunwamba A, Wilson PM, Kumar S, Jacobson RM, Phelan S, Cristiani V, Fan C, Finney Rutten LJ. 2016. Adverse family experiences and obesity in children and adolescents in the United States. Preventive Medicine. 90:148-154.

Maimaitijiang M, Ghulam A, Onésimo Sandoval JS. 2015. Drivers of land cover and land use changes in St. Louis metropolitan area over the past 40 years characterized by remote sensing and census population data. International Journal of Applied Earth Observation and Geoinformation. 35:161–174.

Marsal-Llacuna ML, Colomer-Llinàs J, Meléndez-Frigola J. 2015. Lessons in urban monitoring taken from sustainable and livable cities to better address the smart cities initiatives. Technological Forecasting and Social Change. 90:611–622.

Mesimäki M, Hauru K, Kotze DJ, Lehvävirta S. 2017. Neo-spaces for urban livability? Urbanites' versatile mental images of green roofs in the Helsinki metropolitan area, Finland. Land Use Policy. 61:587-600.

O'Neil-Dunne J, MacFaden S, Royar A. 2014. A versatile, production-oriented approach to high-resolution tree-canopy mapping in urban and suburban landscapes using GEOBIA and data fusion. Remote Sensing. 6:12837–12865.

Onnom W, Tripathi N, Nitivattananon V, Ninsawat S. 2018. Development of a liveable city index (LCI) using multi criteria geospatial modelling for medium class cities in developing countries. Sustainability 10(520). Doi:10.3390/su10020520.
Onojeghuo AO, Onojeghuo AR. 2017. Object-based habitat mapping using very high spatial resolution multispectral and hyperspectral imagery with LiDAR data. Int. Journal of Applied Earth Observation and Geoinformation. 59:79–91.
Staatsbetrieb Geobasisinformation und Vermessung Sachsen (GeoSN). 2012. Orthophotos DOP, Digitales Höhenmodell DGM, Digitales Oberflächenmodell DOM. [accessed 2018 January 18].
http://www.landesvermessung.sachsen.de/
Ordnance Survey of the State of Saxony, Germany. 2012. Acquisition and processing of the data sets digital orthophotos DOP, digital elevation model DEM and digital surface model DSM. (© Staatsbetrieb Geobasisinformation und Vermessung Sachsen). German.
Puissant A, Rougier S, Stumpf A. 2014. Object-oriented mapping of urban trees using Random Forest classifiers. Int. J. Appl. Earth Obs. Geoinf. 26:235–245.
Rashed T, Weeks JR, Stow D, Fugate D. 2005. Measuring temporal compositions of urban morphology through spectral mixture analysis: toward a soft approach to change analysis in crowded cities. International Journal of Remote Sensing. 26(4):699–718.
Rutzinger M, Höfle B, Pfeifer N. 2007. Detection of high urban vegetation with airborne laser scanning data. Proceedings forestsat 2007. Montpellier, France, November, 2007, digital media.
Ryznar RM, Wagner TW. 2001. Using remotely sensed imagery to detect urban change. Viewing Detroit from Space. APA Journal. 67(3):327–336.
Secord J, Zakhor A. 2007. Tree detection in urban regions using aerial LiDAR and image data. IEEE Geoscience and Remote Sensing Letters. 4(2):196–200.
Southworth M. 2016. Learning to make liveable cities. Journal of Urban Design. 21(5):570-573.
Stadt Leipzig, Amt für Statistik und Wahlen, editor. 2012. Statistischer Quartalsbericht IV/2012.
City of Leipzig, Office of Statistics and Elections, editor. 2012. Quarterly Report IV/2012. German.
Stadt Leipzig, Amt für Statistik und Wahlen, editor. 2013a. Statistischer Quartalsbericht II/2013.

City of Leipzig, Office of Statistics and Elections, editor. 2013a. Quarterly Report II/2013. German.
Stadt Leipzig, Amt für Statistik und Wahlen, editor. 2013b. Statistisches Jahrbuch 2013.
City of Leipzig, Office of Statistics and Elections, editor. 2013b. Statistical Yearbook 2013. German.
Stadt Leipzig, Amt für Statistik und Wahlen 2014. Ortsteilkatalog 2014. City of Leipzig, Authority of Statistics and Elections, editor. Official catalogue of local districts. 2014. German.
Stadt Leipzig, Amt für Statistik und Wahlen, editor. 2017. Statistischer Quartalsbericht IV/2017.
City of Leipzig, Office of Statistics and Elections, editor. 2017. Quarterly Report IV/2017. German.
Stadt Leipzig. [date unknown]. Kleingartenanlagen online. [accessed 2018 January 18]. https://www.leipzig.de/freizeit-kultur-und-tourismus/parks-waelder-und-friedhoefe/kleingartenanlagen/
City of Leipzig [date unknown]. Community allotments online. German. [accessed 2018 January 18]. https://www.leipzig.de/freizeit-kultur-und-tourismus/parks-waelder-und-friedhoefe/kleingartenanlagen/
Tole L. 2008. Changes in the built vs. non-built environment in a rapidly urbanizing region: A case study of the Greater Toronto Area. Computers, Environment and Urban Systems. 32:355–364.
[UN] United Nations Department of Economic and Social Affairs/Population Division. 2015a. World Urbanization Prospects: The 2014 Revision. New York:United Nations.
Viitanen J, Kingston R. 2014. Smart cities and green growth: outsourcing democratic and environmental resilience to the global technology sector. Environ. Plan. A 46(4):803e819.
[UN] United Nations Department of Economic and Social Affairs. 2015b. Sustainable Development Goals. 17 Goals to transform our world. [accessed 2018 July 26]. https://sustainabledevelopment.un.org/sdgs.
Wang J, Banzhaf E. 2017. Derive an understanding of Green Infrastructure for the quality of life in cities by means of integrated RS mapping tools. 2017 Joint Urban Remote Sensing Event (JURSE). IEEE - Conference Publications. [accessed 2018 January 19]:[4 p.].

http://www.ieeeexplore.ws/xpl/mostRecentIssue.jsp?filter%3DAND%28p_IS_Number%3A7924526%29&refinements=4223095840&pageNumber=1&resultAction=REFINE.

Weber T. Sloan A, Wolf J. 2006. Maryland's Green Infrastructure Assessment: Development of a comprehensive approach to land conservation. Landscape and Urban Planning. 77:94–110.

[WHO] World Health Organization. 2000. Obesity: preventing and managing the global epidemic. Report of a WHO Consultation. WHO Technical Report Series 894. Geneva: World Health Organization.

Yan WY, Shaker A, El-Ashmawy N. 2015. Urban land cover classification using airborne LiDAR data: A review. Remote Sensing of Environment. 158:295–310.

Yigitcanlar T. 2015. Smart cities: an effective urban development and management model? Australian Planner 52(1):27–34.

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