Fusion of VHR Multispectral and Object Height Data for Urban Environmental Monitoring

CHRISTIAN BERGER[1]

Abstract: Very high resolution (VHR) multispectral and object height data are becoming increasingly available in urban areas. The synergistic utilization of these data holds a large potential for the fine-scale characterization of a city because they are of high descriptive power and non-redundant. However, despite this promising development, detailed and area-wide maps of crucial settlement parameters, like land cover (LC) and urban structure types (USTs), are still lacking in many municipalities. One major reason for this observation is the methodological challenge of turning the wealth of geospatial data into reliable thematic information. My dissertation addresses this problem by (1) developing methods for the fusion of VHR multispectral and object height data, and (2) showcasing the methods' utility in the context of four urban environmental monitoring applications. In this way, both a technical and an applied contribution is made to the fields of urban GIScience and remote sensing.

1 Introduction

Human settlements are complex and dynamic systems having diverse and profound impacts on environmental factors and processes (SCALENGHE & MARSAN 2009). Given the high degree of heterogeneity found in cities, urban environmental monitoring and decision making requires very high resolution (VHR) geospatial data (i.e., ≤5 m spatial resolution) and information products derived thereof (JENSEN & COWEN 1999; KONECNY 1982; WELCH 1982). Thanks to recent technological advancements, reduced production costs, and loosened data policies, this requirement is fulfilled by a growing number of adequate satellite and airborne sensors (BENEDIKTSSON et al. 2012; EHLERS 2009; WENG et al. 2014). VHR multispectral imagery and object height data (e.g., 3D point clouds) are becoming increasingly available in the urbanized regions of the world (LIDAR ONLINE 2014; NOAA 2015; OPENTOPOGRAPHY 2014; SUGARBAKER et al. 2014; USDA 2015). The synergistic utilization of these data sources holds a large potential for the fine-scale characterization of a city because they are of high descriptive power and non-redundant (GAMBA 2014; WENTZ et al. 2014; YAN et al. 2015). However, despite this promising development, detailed, area-wide, and consistent maps of important settlement parameters like urban land cover (LC), urban site characteristics (USCs), and urban structure types (USTs) are still lacking in many municipalities. One reason for this observation is the methodological challenge of turning the wealth of geospatial data into reliable thematic information (LONGLEY et al. 2001; O'NEIL-DUNNE et al. 2013). Accordingly, there is a strong need for accurate and transferable software solutions being able to produce some of the key data sets for human settlement monitoring from VHR multispectral imagery and object height data. My dissertation

[1] Friedrich-Schiller-Universität Jena, Institute of Geography, Department for Earth Observation, Löbdergraben 32, D-07743 Jena, E-Mail: christian.berger@uni-jena.de

(BERGER 2017) aimed at addressing this need. This paper provides a summary of this work for the PFGK18 conference.

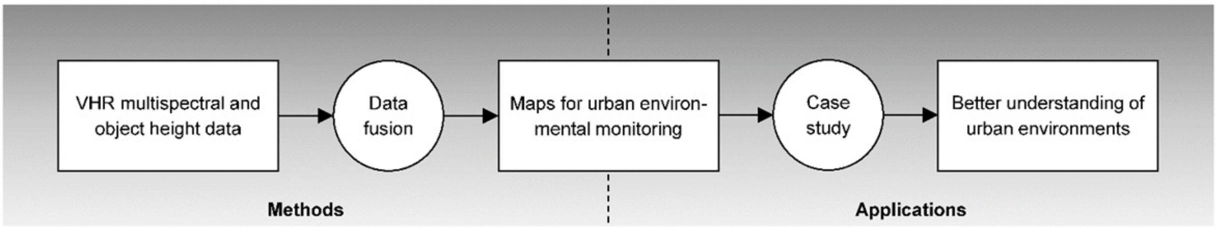

Fig. 1: Scope of my dissertation.

The overall goal of my thesis is to (1) develop methods for the fusion of VHR multispectral imagery and object height data as well as to (2) showcase the methods' utility in the context of four different urban environmental mapping and monitoring applications. The thesis therefore intends to make both a technical ("Methods") and an applied contribution ("Applications") to the fields of urban GIScience and remote sensing (Fig. 1). At the interface of these contributions are urban environmental maps produced by the developed methods and employed within the frame of a predefined case study. More specifically, particular emphasis is put on mapping urban LC, USCs, and USTs, as well as the usage of USCs to study urban land surface temperature (LST) and surface urban heat islands (UHIs; cf. Fig. 3). These settlement parameters were chosen because they are thematically connected, difficult to obtain from other data sources, and of high importance for urban planning and environmental management (CHRYSOULAKIS et al. 2014; JENSEN & COWEN 1999; NICHOL et al. 2007; PAULEIT & BREUSTE 2011; WENTZ et al. 2014). Moreover, they can serve as a starting point to extract further layers of information or to conduct subsequent analyses. From a methodological perspective, much of the research concentrates on geographic object-based image analysis (GEOBIA) (BLASCHKE et al. 2008; BLASCHKE et al. 2014) to achieve the above goal. In addition, the bulk of investigations focuses on test sites located in Germany.

The remainder of this paper is structured as follows. Section 2 defines and differentiates the key terms used in BERGER (2017). Hence, it provides the reader with crucial information for a better understanding of the research conducted. In Section 3, the objectives of my work are deduced from existing research needs and the interconnection between the individual research contributions is introduced by illustrating the practical workflow of the analyses. Section 4 represents the core of this paper. It outlines the research contributions made in BERGER (2017), i.e., the four manuscripts submitted to and accepted by international publication organs with an independent review system. Finally, Section 5 synthesizes the outcomes of my thesis. It summarizes the obtained results and reflects on their implications.

2 Key terms and definitions

In my thesis, each of the four chosen research topics either covers a specific urban environmental phenomenon or a set of settlement parameters belonging together (cf. Fig. 3). The parameters of interest are thematically connected and comprise urban LC, USTs, USCs, and LST. For the sake of clarity, a definition and differentiation of these and related terms is given in the following. Furthermore, the concept behind the expression of urban environmental monitoring is explained.

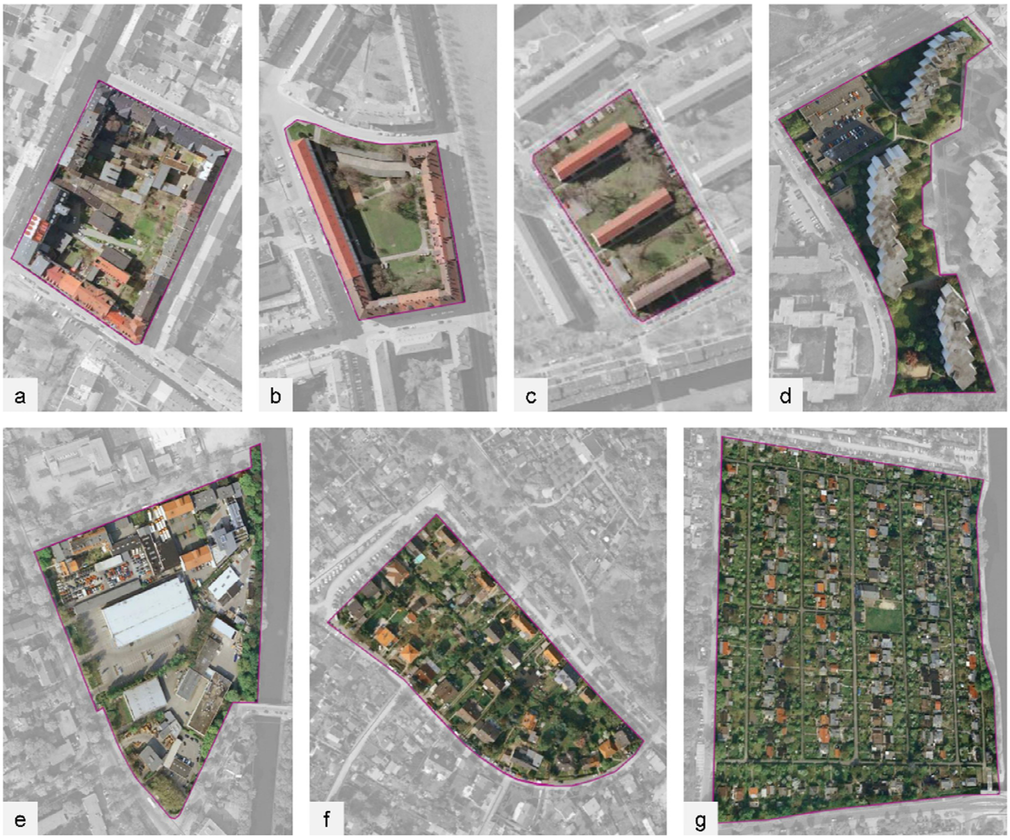

Fig. 2: Visual examples of selected USTs: (a) block development, (b) perimeter block development, (c) row development, (d) high-rise districts, (e) industrial and commercial parks, (f) detached and semi-detached homes, and (g) allotment gardens. Block geometries are highlighted in purple (modified after BOCHOW 2010).

Urban environmental monitoring is conceived here as an umbrella term for mapping, analyzing, and understanding the diverse environmental aspects of a city. As these include, but are not limited to, urban LC, USTs, USCs, and LST, the expression provides an overarching framework to unify the four research subjects selected in my dissertation.

Land cover (LC) is the observed (bio-) physical cover on the Earth's surface (DI GREGORIO 2005; FISHER et al. 2005). Typical examples of (urban) LC elements are buildings, impervious surfaces, trees, grass and shrubs, bare soil, and water (cf. COMBER et al. 2008). An exact definition of LC is crucial because LC is often erroneously confused with land use (LU) (DI GREGORIO 2005).

Land use (LU) is "characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it" (DI GREGORIO 2005:3). Therefore, LU refers to the way the land is utilized by people (i.e., function), while LC can be considered as the "visible evidence" of LU (i.e., form; GIRI 2012:9). Residential, industrial, and commercial areas, parks, sports grounds, and other recreational sites are all common LU types (COMBER et al. 2008).

Urban structure types (USTs) are an ecological concept to divide cities into spatial units of homogenous environmental conditions. A standardized UST classification system does not exist yet (BANZHAF & HÖFER 2008; WURM & TAUBENBÖCK 2010). Existing mapping schemes vary slightly from city to city and usually incorporate a mixture of LU and LC classes (Fig. 2). The spatial delimitation of individual UST entities is based on block geometries, i.e., the streets, railways, and/or topographic features surrounding a block of buildings (cf. GEISS et al. 2011).

Urban site characteristic (USC) is a hypernym specifically defined within my work. The term refers to all kinds of quantitative descriptors that help to map, monitor, and evaluate human settlements. These may include, among others, biophysical proxies like vegetation fraction (VF) and impervious surface area (ISA) (ESCH et al. 2009; RIDD 1995), landscape patterns (BESUSSI et al. 2010; HUANG et al. 2007), 2D and 3D morphology (FINA et al. 2014; YU et al. 2010), and LST (XIAN & CRANE 2006; YUAN & BAUER 2007).

Land surface temperature (LST) is the "average temperature of an element of the exact surface of the Earth calculated from measured radiance" (GILLESPIE 2014). Therefore, it is often referred to as radiometric or skin temperature (LI et al. 2013). LST can either be measured locally by the use of dedicated thermometers or, like in my work, remotely with data acquired by air- and/or spaceborne thermal infrared sensors.

Urban heat islands (UHIs) refer to the observation that cities, towns, and even villages often experience higher air and surface temperatures than their rural surroundings (OKE 1973). They are arguably the most well-documented example of anthropogenic climate modification (ARNFIELD 2003) and can be observed because human settlements have radiative, thermal, aerodynamic, and hydraulic properties that are much different from those of natural landscapes (LANDSBERG 1981).

3 Scientific rationale

An extensive literature survey forms an integral part of my dissertation. The current state of the art in the field of urban environmental monitoring with VHR multispectral and object height data helps identifying past as well as more recent topics of research. But even more importantly, it provides a means to infer those scientific aspects that have gained only little attention so far. This section describes some of the research needs arising from the review conducted in my work and uses them to formulate specific study objectives.

3.1 Research needs

3.1.1 Topic #1: LC mapping

Many studies have already been successful at applying GEOBIA approaches to characterize fine-scale urban LC on the basis of VHR data. However, in spite of previous mapping efforts, only little research in the field has been devoted to building and evaluating robust methods that are capable of processing different sets of VHR multispectral and object height data. So far, existing GEOBIA systems are frequently reported to work well on small spatial subsets (LU et al. 2010;

SALEHI et al. 2012) or for one entire study area (>100 km²) only (PLATT & RAPOZA 2008; WALKER & BLASCHKE 2008). A closer look at the review statistics presented in Table 1 supports this statement. In addition, GEOBIA algorithms often rely on monosensor imagery (TAUBENBÖCK et al. 2010) or even data acquired by one specific sensor (PLATT & RAPOZA 2008; LU et al. 2010; WALKER & BLASCHKE 2008). In order to exploit the full synergistic potential of those VHR multisource data that become increasingly available, suitable fusion techniques and effective practical solutions still

Tab. 1: Selected research deficits arising from the literature review.

Research topic	Review criterion	Number	Percentage
LC mapping	Studies with at least one test site >100 km²	15/115	13.04
	Studies with more than one test site >100 km²	2/115	1.74
	Studies with more than two test sites >100 km²	1/115	0.87
USC assessment	Studies proposing and/or using 2D USCs	78/96	81.25
	Studies proposing and/or using 3D USCs	31/96	32.29
	Studies proposing integrated 2D/3D USCs	4/96	4.17
UST derivation	Studies defining USTs suitable for area-wide mapping	20/38	52.63
	Studies defining USTs suitable for transferable mapping	12/38	31.58
	Studies defining USTs for gap-free and robust mapping	1/38	2.63
USCs vs LST	Studies comparing LST against 2D USCs	119/125	95.20
	Studies comparing LST against 3D USCs	19/125	15.20
	Studies analyzing integrated 2D/3D USCs	0/125	0.00

need to be developed and rigorously tested. The latter requires an in-depth assessment of their performance with regard to classification accuracy as well as spatial, temporal, and sensor-related transferability. An adequate experimental setup should therefore comprise large volumes of VHR data acquired at varying sensing schemes and covering different urban areas with distinct physical structures.

3.1.2 Topic #2: USC assessment

Due to the 3D nature of human settlements, urban environmental monitoring should rely on information sources that account not only for the horizontal spatial dimensions of a city, but also for its vertical spatial dimension. This enables an integrated and more holistic assessment of the "builtscape" (GAMBA et al. 2004). In order to meet these requirements, various 2D and 3D USCs have been proposed and used to date. This holds especially true for the field of urban density mapping by means of remote sensing data and methods. However, despite these developments, it has to be kept in mind that each of the available USCs covers different and distinct features of a city and therefore addresses only specific aspects of human settlement density. This implies that there is a lack of comprehensive USCs being able to interrelate existing and possibly new spatial indicators for a more holistic assessment of density patterns in urban environments. Exceptions to this observation are limited. As Table 1 shows, only four out of 96 reviewed studies (i.e., ca. 4%) put a focus on developing these advanced metrics. Examples include the fuzzy urban index (GOPAL et al. 2016), the Spacematrix (SALOMONS & BERGHAUSER PONT 2012), and a few indices related to urban green (GUPTA et al. 2012; LIU et al. 2015; TOMPALSKI & WEZYK 2012). Apart from these exceptions, there is still a need for integrated spatial indicators taking full advantage of a combination of 2D and 3D USCs to estimate urban density in its entirety. Their implementation would be straightforward provided that detailed urban LC information as well as VHR object height data are available.

3.1.3 Topic #3: UST derivation

Besides urban LC, GEOBIA approaches have also proven to be successful in the context of several independent UST studies. However, they are part of a relatively young field of science (starting with STEINNOCHER et al. 2001) and there are still some research aspects deserving more attention.

First, existing class hierarchies and definitions are insufficient. To date, investigations are often restricted to a limited number of map categories (STEINIGER et al. 2008; WALDE et al. 2014; WURM & TAUBENBÖCK 2010) or a small spatial subset of the city under consideration (HEIDEN et al. 2012; HU & WANG 2013; LACKNER & CONWAY 2008). Furthermore, even though some of the earlier works deal with an extended set of classes, they rely on site-specific UST legends (e.g., by referring to historic functional use) that are not applicable to other urban areas (cf. BANZHAF & HÖFER 2008; GEISS et al. 2011). Table 1 reflects the above conceptual issues. More specifically, it highlights that there is only one relevant publication (WURM & TAUBENBÖCK 2010) in which UST classes are defined and derived that meet the requirements of map completeness and standardization (BANZHAF & HÖFER 2008; BREUSTE 2010). In order to enable the generation of area-wide (gap-free) and comparable (uniform) UST maps, there is a need for improved class hierarchies with greater depth, enhanced transferability, and, thus, broader applicability. The development of a comprehensive, yet generic UST map key is a prerequisite for the operational monitoring of cities and should therefore be an integral preparatory step within any future study in the field.

Second, the potential of many USCs remains unknown. Based on the form and function of the desired UST categories, a qualitative description and parametrization of all target classes is frequently performed in advance. As a consequence, the majority of existing classification schemes focuses on the extraction of features that have been subjectively predefined and are assumed to be effective according to the conceptual model for each UST of interest (BANZHAF & HÖFER 2008; WURM & TAUBENBÖCK 2010). Such an approach suffers from several drawbacks. One of them is that only a small fraction of potentially useful USCs is considered. Those site properties with no obvious link to any of the anticipated USTs are neglected. Another disadvantage is that the individual and combined descriptive power of all theoretically available USCs is not systematically assessed. Rather, an isolated examination and utilization of apparent physiognomic urban block characteristics takes place. This is one of the reasons why a lot of methods are fairly successful at deriving morphologically distinct USTs but less appropriate for an accurate differentiation of the more common and structurally similar USTs (WURM & TAUBENBÖCK 2010).

To overcome these limitations, the proposed strategies for extracting and selecting USCs need to be reconsidered. For this purpose, a promising approach is to systematically retrieve all kinds of land surface parameters known from the urban remote sensing literature without making specific assumptions about their avail. While some of these parameters may already be established, others, like landscape metrics (e.g., patch density) and several 3D USCs (e.g., VV2BV), may have never been used before in the context of UST mapping. After the derivation of these variables, it is crucial to statistically evaluate their suitability in the course of a dedicated, importance-based assessment. The latter facilitates the identification of their individual potential as well as their synergies.

In summary, the above suggestions ensure a comprehensive analysis and objective comparison of USCs for a better characterization of USTs. Their implementation would help compiling a new set of UST features, developing more sophisticated class descriptions, and improving previously achieved mapping accuracies.

3.1.4 Topic #4: USCs vs LST

A considerable amount of research has already been directed towards understanding the links between USCs and LST. Most notably, a lot of emphasis has been placed on the 2D features of a city. Table 1 confirms this tendency by indicating that 119 out of 125 publications (i.e., ca. 95%) deal with 2D metrics. In contrast to that, 3D (15%) and integrated 2D/3D USCs (0%) still remain largely unexplored although their impact on the urban climate is unquestioned (OKE 1981; UNGER 2004) and their area-wide calculation has become feasible thanks to the increased availability of appropriate remote sensing data (cf. Section 1). Except for a few cases (e.g., CHUN & GULDMANN 2014; NASSAR et al. 2016; SCARANO & SOBRINO 2015), there is still a lack of studies relating 2D, 3D, and integrated 2D/3D USCs to LST (cf. MALLICK et al. 2013; NGIE et al. 2014; VOOGT & OKE 2003). Moreover, previous research findings are often based on the analysis of a single study area, a limited number of USCs, and/or only a few LST scenes acquired within specific seasons (e.g., LIU & ZHANG 2011; MAIMAITIYIMING et al. 2014; REN et al. 2013; WENG et al. 2004; XIAO et al. 2008; ZHANG et al. 2009). In order to obtain a more complete picture of the connection between USCs and LST, more comprehensive investigations still need to be undertaken.

3.2 Study objectives

In accordance with the overall goal defined above (cf. Section 1) and motivated by the four research needs, the specific objectives of my thesis are defined as follows:

1. *Robust extraction of urban LC information*, including the
    - development and application of a robust GEOBIA approach to extract detailed and accurate urban LC information from VHR multispectral and object height data;
    - critical evaluation of the proposed method with regard to its performance for and transferability to different study areas and various sets of VHR multisensor data.
2. *Integrated assessment of 2D and 3D USCs*, including the
    - design and implementation of a new spatial indicator to integratively assess urban density by taking into account the horizontal and vertical key characteristics of a city;
    - critical evaluation of the proposed metric's plausibility and qualification to estimate human settlement density and its distinct spatial patterns for different urban LU types.
3. *Automated derivation of UST maps*, including the

- development and application of a generic GEOBIA approach for an area-wide and automated derivation of USTs from VHR multispectral and object height data;
- critical evaluation of the proposed method regarding classification accuracy, workflow automation, and preparedness for future UST mapping and monitoring tasks.

4. *Detailed analysis of USC–LST links*, including the
   - calculation and analysis of 2D, 3D, and integrated 2D/3D USCs as potential predictors of urban LST as well as potential indicators of the surface UHI phenomenon;
   - detailed inspection of the observed relationships as well as their spatio-temporal dependencies by designing and implementing a comprehensive experimental setup.

Figure 3 provides an overview of the four chosen research topics and shows their thematic interconnection. Moreover, it illustrates the conceptual workflow of the practical investigations conducted within my work and outlines the general research agenda.

4 Research contributions

This section represents the core of my dissertation. It outlines the research contributions made in BERGER (2017), i.e., the four manuscripts submitted to and accepted by international publication organs with an independent review system.

4.1 Robust extraction of urban LC information

In BERGER et al. (2013b), a robust GEOBIA approach was developed to extract detailed and accurate urban LC information from VHR multispectral imagery and object height data. Special attention was paid to the critical evaluation of the proposed method with regard its performance for and applicability to different test sites and various sets of VHR multisensor data. For this purpose, the experimental setup of the study included three cities featuring different physical structures, four sets of VHR optical and light detection and ranging (LiDAR) data, as well as statistical measures to enable the assessment of classification accuracies and methodological transferability. The study results highlight the great potential of the described approach for accurate, robust, and large-area mapping of urban environments. User's and producer's accuracies observed for all maps were almost consistently above 80%, and in many cases even above 90%. Only few larger class-specific errors occurred mainly due to the rather simple (yet effective) assumptions on which the method is based. The presented feature extraction workflow can therefore be used as a template for or starting point of future urban LC mapping efforts.

4.2 Integrated assessment of 2D and 3D USCs

In BERGER et al. (2013a), a new spatial indicator was designed, implemented, and successfully demonstrated within the framework of the 2012 IEEE GRSS Data Fusion Contest. The aim was to integratively assess urban density by taking into account some of the 2D and 3D key characteristics of a city. To this end, fusion of WorldView-2 and LiDAR data was performed. In a first step, basic urban LC information was extracted from the preprocessed input data sets using the GEOBIA approach developed in BERGER et al. (2013b). The LC map was then utilized in combination with the object height information provided by the LiDAR data to infer urban density. The resulting map and statistics underscore the plausibility and qualification of the proposed metric as a useful measure to evaluate human settlement density and its distinct spatial patterns for different types of urban LU. By taking into account all three spatial dimensions of the urban environment, an integrated and more holistic assessment of the "builtscape" is enabled. To further enhance the transparency of the study, a dedicated geoportal was set up that visualizes all input data, final results, by-products, and ancillary information (EBERLE & BERGER 2012).

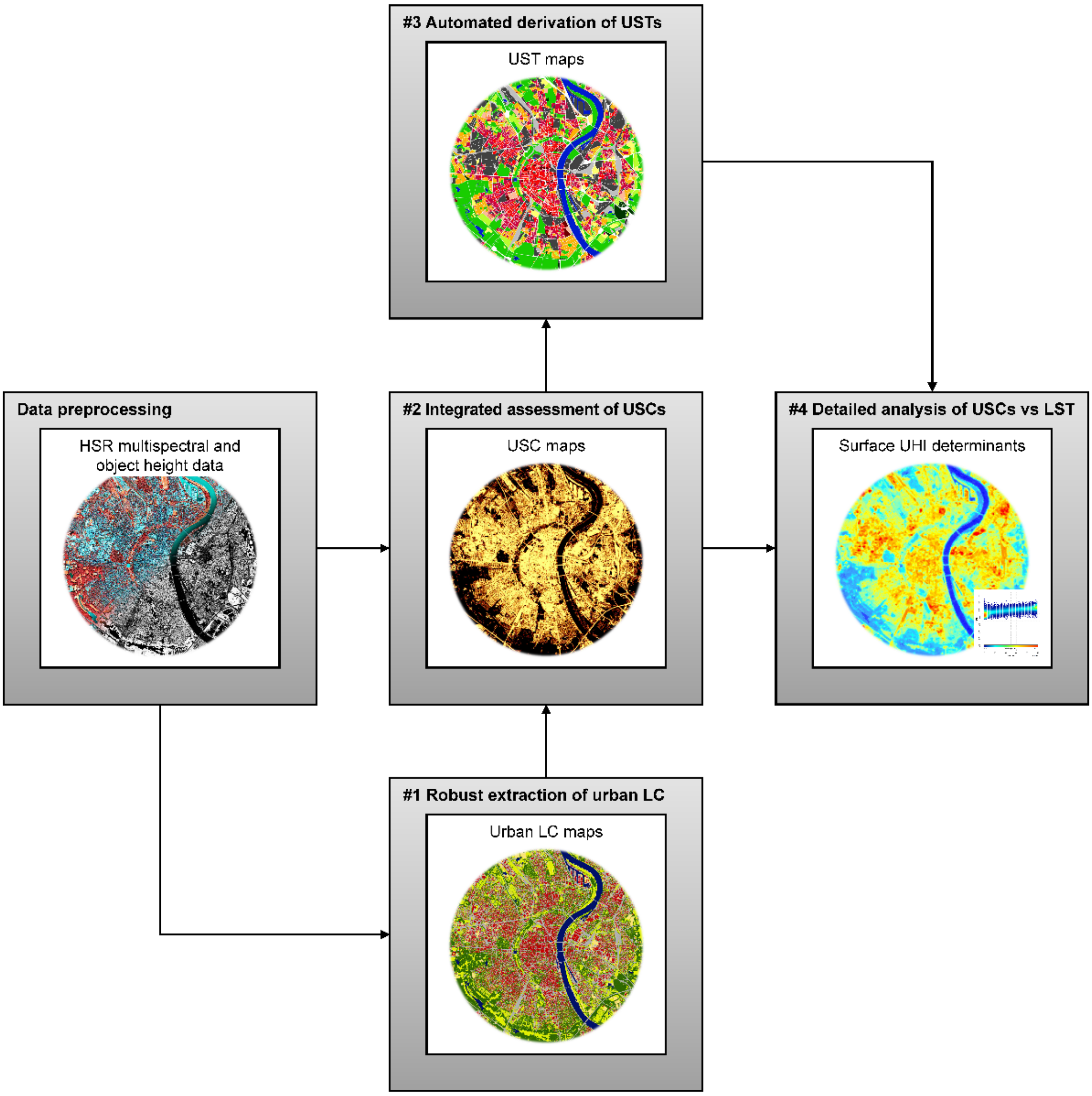

Fig. 3: Practical workflow of my thesis and links between the four chosen research topics.

4.3 Automated derivation of UST maps

In VOLTERSEN et al. (2014), a generic GEOBIA system was developed for an area-wide, automated derivation of USTs. Synergistic use was made of VHR multispectral and object height data acquired by the airborne UltraCamX sensor over the city of Berlin, Germany. Initially, urban LC information was extracted from the preprocessed input data by means of the classification scheme presented in BERGER et al. (2013b). The LC map was then employed together with the UltraCamX object heights to infer a comprehensive set of 2D, 3D, and integrated 2D/3D USCs. In a third step, the importance of the generated image features was evaluated by the random forests machine learning algorithm. Finally, the experiences gained from the assessment were used to build improved UST class descriptions. The latter were based on both well-established as well as more recently introduced USCs, such as the urban density metric proposed in BERGER et al. (2013a). The analysis results and the produced map emphasize the suitability of the described method with regard to classification accuracy, workflow automation, and preparedness in the context of future UST mapping and monitoring tasks. The UST mapping method ranked second in the Student Paper Competition of the JURSE conference in Lausanne, Switzerland (VOLTERSEN et al. 2015).

4.4 Detailed analysis of USC–LST links

In BERGER et al. (2017), the relationship between USCs and LST was studied. Focus was laid on an extensive comparison of 2D, 3D, and integrated 2D/3D USCs as potential predictors of urban LST as well as potential indicators of the surface UHI effect. In addition to the comparison of USCs, the spatio-temporal dependencies of their relation to LST were examined. For this purpose, the experimental setup included two study areas, 26 USCs, and 16 LST scenes covering four seasons. The results of the study demonstrate that the linkage between USCs and LST sensed at small scan angles is not stronger when 3D or integrated 2D/3D parameters are considered. Even though they may offer more holistic representations of the urban landscape, they were consistently outperformed by some of the most widely-used 2D metrics. The analysis of spatial dependencies revealed that the USC–LST interplay does not only differ between, but also within the two test sites. This is due to their distinct geographies, with urban form and compactness, green spaces and street trees, and the structural composition of LC elements being some of the determining factors. The examination of temporal dependencies yielded that the association between USCs and LST is fairly stable over time, but can be subject to larger inter- and intra-season variations for different reasons, including the season of acquisition, vegetation phenology, and meteorological conditions. Since previous research was based on the analysis of a single study area, a limited number of (mainly 2D) USCs, and/or only few LST scenes acquired in specific seasons, the findings of the study provide researchers and practitioners with a more complete picture of the USC–LST relationship.

5 Synthesis

VHR multispectral and object height data are becoming increasingly available in urban areas. The synergistic utilization of these data sets holds a large potential for the fine-scale characterization of a city because they are of high descriptive power and non-redundant.

However, despite this promising development, detailed and area-wide maps of important settlement parameters, like LC, USCs, and USTs, are still lacking in many urban areas. One major reason for this observation is the methodological challenge of turning the wealth of geospatial data into reliable thematic information. Accordingly, there is a strong need for accurate and transferable software solutions being able to produce some of the key data sets for human settlement monitoring from VHR multispectral and object height data. My dissertation (BERGER 2017) aimed at addressing this need. The present paper provided a summary of this work for the PFGK18 conference.

My thesis focused on (1) developing methods for the fusion of VHR multispectral and object height data as well as on (2) showcasing the methods' utility in the context of four different urban environmental mapping and monitoring applications. It therefore aimed at making both a technical and an applied contribution to the fields of urban GIScience and remote sensing. More specifically, particular emphasis was put on mapping urban LC, USCs, and USTs, as well as the usage of USCs to study urban LST and the surface UHI effect. These settlement parameters were chosen because they are thematically connected, difficult to obtain from other data sources, and of high relevance for urban planning and environmental management. To meet the above goal, a comprehensive literature review was conducted in advance. The review helped identifying current deficits within

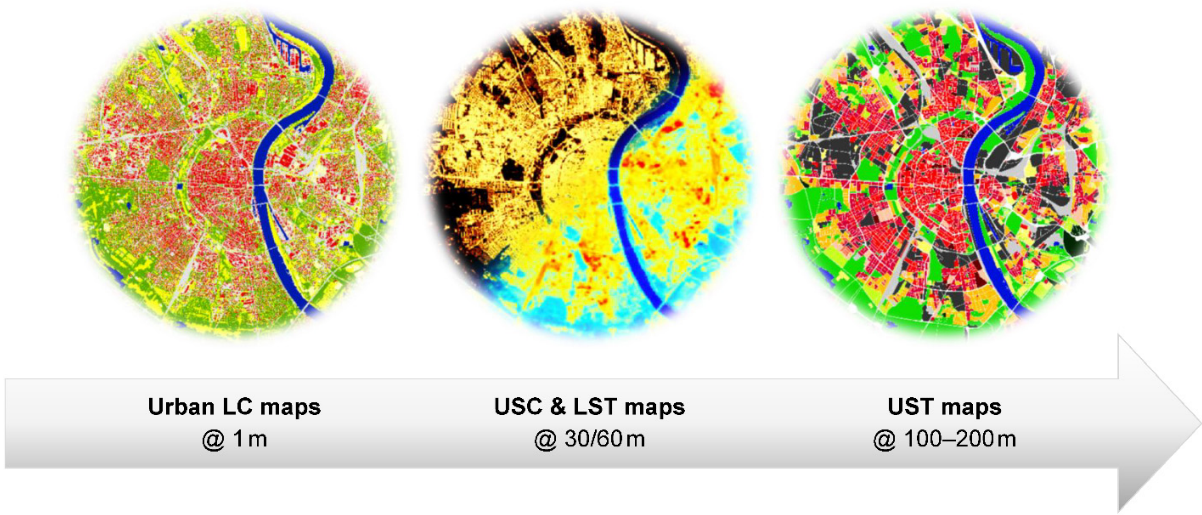

Fig. 4: Spatial resolution of the urban environmental maps produced.

the chosen research fields and led to the formulation of specific objectives. The latter determined the practical agenda of my work, comprising an overall number of four published studies.

With the first three studies, my dissertation has introduced a suite of GEOBIA approaches that build on top of each other. These methods exploit the synergies among VHR multisource data and proved to be suitable for an accurate, yet robust characterization of different settlement parameters, including urban LC, USCs, and USTs. From a geographical perspective, much of my research has concentrated on test sites located in Germany. However, the described classification and analysis schemes are expected to work well for any other Western culture city as long as the available multispectral and object height data meet some basic requirements (e.g., VHR imagery with four standard spectral bands and 3D data with ≥4 points per m²). Fortunately, these requirements are increasingly fulfilled thanks to a growing number of those VHR multisensor data becoming more and more available in the urbanized regions of the world.

Within the final study of my thesis, the methods developed earlier were effectively employed to produce thematic maps at three spatial scales (Fig. 4). These maps were then used to examine the complex spatio-temporal relation between USCs and LST. This investigation was exemplary for showing that the multilevel information products generated by the fusion of VHR multispectral and object height data are highly versatile and can be reutilized in the context of different follow-up applications. It also illustrates that an individual or joint integration of these maps into other experiments holds the potential for advancing urban research at comparable, coarser, or finer spatial scales. In this sense, the work in BERGER (2017) has provided a continuous and consistent methodological framework for local to regional mapping and monitoring of urban environmental phenomena.

6 Literature

ARNFIELD, A., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. Int J Climatol **23** (1), 1–26.

BANZHAF, E. & HÖFER, R., 2008: Monitoring urban structure types as spatial indicators with CIR aerial photographs for a more effective urban environmental management. IEEE J Sel Top Appl Earth Obs Remote Sens **1** (2), 129–138.

BENEDIKTSSON, J.; CHANUSSOT, J. & MOON, W., 2012: Very high-resolution remote sensing: Challenges and opportunities. P IEEE **100** (6), 1907–1910.

BERGER, C., 2017: Fusion of High Spatial Resolution Multispectral Object Height Data for Urban Environmental Monitoring. <https://www.researchgate.net/publication/318983054_Fusion_of_High_Spatial_Resolution_Multispectral_Object_Height_Data_for_Urban_Environmental_Monitoring> (last accessed on 2018-01-23).

BERGER, C.; ROSENTRETER, J.; VOLTERSEN, M.; BAUMGART, C.; SCHMULLIUS, C. & HESE, S., 2017: Spatio-temporal analysis of the relationship between 2D/3D urban site characteristics and land surface temperature. Remote Sens Environ **193** (C), 225–243.

BERGER, C.; VOLTERSEN, M.; ECKARDT, R.; EBERLE, J.; HEYER, T.; SALEPCI, N.; HESE, S.; SCHMULLIUS, C.; TAO, J.; AUER, S.; BAMLER, R.; EWALD, K; GARTLEY, M.; JACOBSON, J.; BUSWELL, A.; DU, Q. & PACIFICI, F., 2013a: Multi-modal and multi-temporal data fusion: Outcome of the 2012 GRSS Data Fusion Contest. IEEE J Sel Top Appl Earth Obs Remote Sens **6** (3), 1324–1340.

BERGER, C.; VOLTERSEN, M.; HESE, S.; WALDE, I. & SCHMULLIUS, C., 2013b: Robust extraction of urban land cover information from HSR multi-spectral and LiDAR data. IEEE J Sel Top Appl Earth Obs Remote Sens **6** (5), 2196–2211.

BESUSSI, E.; CHIN, N.; BATTY, M. & LONGLEY, P., 2010: The structure and form of urban settlements. In: RASHED, T. & JÜRGENS, C., Eds.: Remote sensing of urban and suburban areas. Remote sensing and digital image processing 10. Dordrecht, The Netherlands: Springer, 13–31.

BLASCHKE, T.; HAY, G.; KELLY, M.; LANG, S.; HOFMANN, P.; ADDINK, E.; QUEIROZ FEITOSA, R.; VAN DER MEER, F.; VAN DER WERFF, H.; VAN COILLIE, F. & TIEDE, D., 2014: Geographic object-based image analysis – Towards a new paradigm. ISPRS J Photogramm **87**, 180–191.

BLASCHKE, T.; LANG, S. & HAY, G., Eds., 2008: Object-based image analysis for remote sensing. Spatial concepts for knowledge-driven remote sensing applications. Berlin, Germany: Springer.

BOCHOW, M., 2010: Automatisierungspotenzial von Stadtbiotopkartierungen durch Methoden der Fernerkundung. PhD thesis. Osnabrück, Germany: Fachbereich Mathematik/Informatik, Universität Osnabrück.

BREUSTE, J., 2010: Challenges and problems of implementing landscape ecological knowledge in practice – The case of urban development. The Problems of Landscape Ecology **28**, 23–32.

CHRYSOULAKIS, N.; FEIGENWINTER, C.; TRIANTAKONSTANTIS, D.; PENYEVSKIY, I.; TAL, A.; PARLOW, E.; FLEISHMAN, G.; DÜZGÜN, S.; ESCH, T. & MARCONCINI, M., 2014: A conceptual list of indicators for urban planning and management based on Earth observation. ISPRS Int J Geo-Inf **3** (3), 980–1002.

CHUN, B. & GULDMANN, J., 2014: Spatial statistical analysis and simulation of the urban heat island in high-density central cities. Landscape Urban Plan **125**, 76–88.

COMBER, A.; WADSWORTH, R. & FISHER, P., 2008: Using semantics to clarify the conceptual confusion between land cover and land use: The example of 'forest'. J Land Use Sci **3** (2–3), 185–198.

DI GREGORIO, A., 2005: Land cover classification system (LCCS). Classification concepts and user manual. Software version 2. FAO environment and natural resources service series 8. Rome, Italy: FAO.

EBERLE, J. & BERGER, C., 2012: Urban density (UD) mapping results for the City of San Francisco (Geoportal). Contribution to the 2012 IEEE GRSS Data Fusion Contest. <http://sf.maps.essi-blog.org/> (last accessed on 2018-01-23).

EHLERS, M., 2009: Future EO sensors of relevance – Integrated perspective for global urban monitoring. In: GAMBA, P. & HEROLD, M., Eds.: Global mapping of human settlement. Boca Raton, FL: CRC Press, 321–337.

ESCH, T.; HIMMLER, V.; SCHORCHT, G.; THIEL, M.; WEHRMANN, T.; BACHOFER, F.; CONRAD, C.; SCHMIDT, M. & DECH, S., 2009: Large-area assessment of impervious surface based on integrated analysis of single-date Landsat-7 images and geospatial vector data. Remote Sens Environ **113** (8), 1678–1690.

FINA, S.; KREHL, A.; SIEDENTOP, S.; TAUBENBÖCK, H. & WURM, M., 2014: Dichter dran! Neue Möglichkeiten der Vernetzung von Geobasis-, Statistik- und Erdbeobachtungsdaten zur räumlichen Analyse und Visualisierung von Stadtstrukturen mit Dichteoberflächen und -profilen. Raumforsch Raumordn **72** (3), 179–194.

FISHER, P.; COMBER, A. & WADSWORTH, R., 2005: Land use and land cover: Contradiction or complement. In: FISHER, P. & UNWIN, D., Eds.: Re-presenting GIS. Hoboken, NJ: John Wiley & Sons, 85–98.

GAMBA, P., 2014: Image and data fusion in remote sensing of urban areas: Status issues and research trends. Int J Image Data Fusion **5** (1), 2–12.

GAMBA, P.; DELL'ACQUA, F.; CISOTTA, F. & LISINI, G., 2004: High resolution InSAR ”builtscape” improvement using LiDAR as ancillary data. Proceedings of IGARSS, 20–24 September, Anchorage, AK, 1808–1811.

GEISS, C.; TAUBENBÖCK, H.; WURM, M.; ESCH, T.; NAST, M.; SCHILLINGS, C. & BLASCHKE, T., 2011: Remote sensing-based characterization of settlement structures for assessing local potential of district heat. Remote Sens **3** (7), 1447–1471.

GILLESPIE, A., 2014: Land surface temperature. In: NJOKU, E., Ed.: Encyclopedia of remote sensing. Encyclopedia of Earth sciences series. New York City, NY: Springer, 314–319.

GIRI, C., 2012: Brief overview of remote sensing of land cover. In: WENG, Q., Ed.: Remote sensing of land use and land cover. Remote sensing applications. Boca Raton, FL: CRC Press, 3–12.

GOPAL, S.; TANG, X.; PHILLIPS, N.; NOMACK, M.; PASQUARELLA, V. & PITTS, J., 2016: Characterizing urban landscapes using fuzzy sets. Comput Environ Urban **57**, 212–223.

GUPTA, K.; KUMAR, P.; PATHAN, S. & SHARMA, K., 2012: Urban Neighborhood Green Index – A measure of green spaces in urban areas. Landscape Urban Plan **105** (3), 325–335.

HEIDEN, U.; HELDENS, W.; ROESSNER, S.; SEGL, K.; ESCH, T. & MUELLER, A., 2012: Urban structure type characterization using hyperspectral remote sensing and height information. Landscape Urban Plan **105** (4), 361–375.

HU, S. & WANG, L., 2013: Automated urban land-use classification with remote sensing. Int J Remote Sens **34** (3), 790–803.

HUANG, J.; LU, X. & SELLERS, J., 2007: A global comparative analysis of urban form: Applying spatial metrics and remote sensing. Landscape Urban Plan **82** (4), 184–197.

JENSEN, J. & COWEN, D., 1999: Remote sensing of urban/suburban infrastructure and socio-economic attributes. Photogramm Eng Rem S **65** (5), 611–622.

KONECNY, G.; SCHUHR, W. & WU, J., 1982: Untersuchungen über die Interpretierbarkeit von Bildern unterschiedlicher Sensoren und Plattformen für die kleinmaßstäbige Kartierung. Bildmessung und Luftbildwesen **50**, 187–200.

LACKNER, M. & CONWAY, T., 2008: Determining land-use information from land cover through an object-oriented classification of Ikonos imagery. Can J Remote Sens **34** (1–2), 77–92.

LANDSBERG, H., 1981: The urban climate. International geophysics series 28. New York, NY: Academic Press.

LI, Z.; TANG, B.; WU, H.; REN, H.; YAN, G.; WAN, Z.; TRIGO, I. & SOBRINO, J., 2013: Satellite-derived land surface temperature: Current status and perspectives. Remote Sens Environ **131**, 14–37.

LIDAR ONLINE, 2014: Lidar Online – Worldwide LiDAR data and geoservices. <https://www.lidar-online.com/> (last accessed on 2018-01-23).

LIU, L. & ZHANG, Y., 2011: Urban heat island analysis using the Landsat TM data and ASTER data: A case study in Hong Kong. Remote Sens **3** (7), 1535–1552.

LIU, Y.; MENG, Q.; ZHANG, J.; ZHANG, L.; JANCSO, T. & VATSEVA, R., 2015: An effective Building Neighborhood Green Index model for measuring urban green space. Int J Dig Earth **9** (4), 387–409.

LONGLEY, P.; BARNSLEY, M. & DONNAY, J., 2001: Remote sensing and urban analysis: A research agenda. In: DONNAY, J.; BARNSLEY, M. & LONGLEY, P., Eds.: Remote sensing and urban analysis. GISDATA 9. Boca Raton, FL: CRC Press, 249–262.

LU, D.; HETRICK, S. & MORAN, E., 2010: Land cover classification in a complex urban-rural landscape with QuickBird imagery. Photogramm Eng Rem S **76** (10), 1159–1168.

MAIMAITIYIMING, M.; GHULAM, A.; TIYIP, T.; PLA, F.; LATORRE-CARMONA, P.; HALIK, Ü.; SAWUT, M. & CAETANO, M., 2014: Effects of green space spatial pattern on land surface temperature: Implications for sustainable urban planning and climate change adaptation. ISPRS J Photogramm **89**, 59–66.

MALLICK, J.; RAHMAN, A. & SINGH, C., 2013: Modeling urban heat islands in heterogeneous land surface and its correlation with impervious surface area by using night-time ASTER satellite data in highly urbanizing city, Delhi- India. Adv Space Res **52** (4), 639–655.

NASSAR, A.; BLACKBURN, G. & WHYATT, J., 2016: Dynamics and controls of urban heat sink and island phenomena in a desert city: Development of a local climate zone scheme using remotely-sensed inputs. Int J Appl Earth Obs **51**, 76–90.

NGIE, A.; ABUTALEB, K.; AHMED, F.; DARWISH, A. & AHMED, M., 2014: Assessment of urban heat island using satellite remotely sensed imagery: A review. S Afr Geogr J **96**, 1–17.

NICHOL, J.; KING, B.; QUATTROCHI, D.; DOWMAN, I.; EHLERS, M. & DING, X., 2007: Earth observation for urban planning and management. State of the art and recommendations for application of Earth observation in urban planning. Photogramm Eng Rem S **73** (9), 973–979.

NOAA (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION), 2015: Digital coast data access viewer. <http://coast.noaa.gov/dataviewer/#> (last accessed on 2018-01-23).

OKE, T., 1973: City size and the urban heat island. Atmos Environ **7** (8), 769–779.

OKE, T., 1981: Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations. J Climatol **1** (3), 237–254.

O'NEIL-DUNNE, J.; MACFADEN, S.; ROYAR, A. & PELLETIER, K., 2013: An object-based system for LiDAR data fusion and feature extraction. Geocarto Int **28** (3), 227–242.

OPENTOPOGRAPHY, 2014: OpenTopography – A portal to high-resolution topography data and tools. <http://www.opentopography.org/> (last accessed on 2018-01-23).

PAULEIT, S. & BREUSTE, J., 2011: Land-use and surface-cover as urban ecological indicators. In: NIEMELÄ, J.; BREUSTE, J.; ELMQVIST, T.; GUNTENSPERGEN, G.; JAMES, P. & MCINTYRE, N., Eds.: Urban ecology: Patterns, processes, and applications. Oxford, UK: Oxford University Press, 19–30.

PLATT, R. & RAPOZA, L., 2008: An evaluation of an object-oriented paradigm for land use/land cover classification. Prof Geogr **60** (1), 87–100.

REN, Z.; HE, X.; ZHENG, H.; ZHANG, D.; YU, X.; SHEN, G. & GUO, R., 2013: Estimation of the relationship between urban park characteristics and park cool island intensity by remote sensing data and field measurement. Forests **4** (4), 868–886.

RIDD, M., 1995: Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: Comparative anatomy for cities. Int J Remote Sens **16** (12), 2165–2185.

SALEHI, B.; ZHANG, Y.; ZHONG, M. & DEY, V., 2012: Object-based classification of urban areas using VHR imagery and height points ancillary data. Remote Sens **4** (8), 2256–2276.

SALOMONS, E. & BERGHAUSER PONT, M., 2012: Urban traffic noise and the relation to urban density, form, and traffic elasticity. Landscape Urban Plan **108** (1), 2–16.

SCALENGHE, R. & MARSAN, F., 2009: The anthropogenic sealing of soils in urban areas. Landscape Urban Plan **90** (1), 1–10.

SCARANO, M. & SOBRINO, J., 2015: On the relationship between the sky view factor and the land surface temperature derived by Landsat-8 images in Bari, Italy. Int J Remote Sens **36** (19–20), 4820–4835.

STEINIGER, S.; LANGE, T.; BURGHARDT, D. & WEIBEL, R., 2008: An approach for the classification of urban building structures based on discriminant analysis techniques. T GIS **12** (1), 31–59.

STEINNOCHER, K.; BAUER, T.; KÖSTL, M. & KRESSLER, F., 2001: Beobachtung von Stadtentwicklung mit Fernerkundung. Applikationen und Innovationen. Österreichische Zeitschrift für Vermessung und Geoinformation **89** (3), 145–148.

SUGARBAKER, L.; CONSTANCE, E.; HEIDEMANN, H.; JASON, A.; LUKAS, V.; SAGHY, D. & STOKER, J., 2014: The 3D Elevation Program initiative – A call for action. Circular 1399. Reston, VA: U.S. Geological Survey.

TAUBENBÖCK, H.; ESCH, T.; WURM, M.; ROTH, A. & DECH, S., 2010: Object-based feature extraction using high spatial resolution satellite data of urban areas. J Spat Sci **55** (1), 117–132.

TOMPALSKI, P. & WEZYK, P., 2012: LiDAR and VHRS data for assessing living quality in cities – An approach based on 3D indices. Int Arch Photogramm Remote Sens Spatial Inf Sci **XXXIX-B6**, 173–176.

UNGER, J., 2004: Intra-urban relationship between surface geometry and urban heat island: Review and new approach. Clim Res **27** (3), 253–264.

USDA (UNITED STATES DEPARTMENT OF AGRICULTURE), 2015: Geospatial data gateway. <https://gdg.sc.egov.usda.gov/GDGOrder.aspx> (last accessed on 2018-01-23).

VOLTERSEN, M.; BERGER, C.; HESE, S. & SCHMULLIUS, C., 2014: Object-based land cover mapping and comprehensive feature calculation for an automated derivation of urban structure types at block level. Remote Sens Environ **154**, 192–201.

VOLTERSEN, M.; BERGER, C.; HESE, S. & SCHMULLIUS, C., 2015: Expanding an urban structure type mapping approach from a subarea to the entire city of Berlin. Proceedings of the 2015 Joint Urban Remote Sensing Event, March 30–April 01, Lausanne, Switzerland, 1–4.

VOOGT, J. & OKE, T., 2003: Thermal remote sensing of urban climates. Remote Sens Environ **86** (3), 370–384.

WALDE, I.; HESE, S.; BERGER, C. & SCHMULLIUS, C., 2014: From land cover-graphs to urban structure types. Int J Geogr Inf Sci **28** (3), 584–609.

WALKER, J. & BLASCHKE, T., 2008: Object-based land-cover classification for the Phoenix metropolitan area: Optimization vs. transportability. Int J Remote Sens **29** (7), 2021–2040.

WELCH, R., 1982: Spatial resolution requirements for urban studies. International Journal of Remote Sensing **3** (2), 139–146.

WENG, Q., Ed., 2014: Global urban monitoring and assessment through Earth observation. Remote sensing applications. Boca Raton, FL: CRC Press.

WENG, Q.; LU, D. & SCHUBRING, J., 2004: Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies. Remote Sens Environ **89** (4), 467–483.

WENTZ, E.; ANDERSON, S.; FRAGKIAS, M.; NETZBAND, M.; MESEV, V.; MYINT, S.; QUATTROCHI, D.; RAHMAN, A. & SETO, K., 2014: Supporting global environmental change research: A review of trends and knowledge gaps in urban remote sensing. Remote Sens **6** (5), 3879–3905.

WURM, M. & TAUBENBÖCK, H., 2010: Fernerkundung als Grundlage zur Identifikation von Stadtstrukturtypen. In: TAUBENBÖCK, H. & DECH, S., Eds.: Fernerkundung im urbanen Raum. Erdbeobachtung auf dem Weg zur Planungspraxis. Darmstadt, Germany: Wissenschaftliche Buchgesellschaft, 94–103.

XIAN, G. & CRANE, M., 2006: An analysis of urban thermal characteristics and associated land cover in Tampa Bay and Las Vegas using Landsat satellite data. Remote Sens Environ **104** (2), 147–156.

XIAO, R.; WENG, Q.; OUYANG, Z.; LI, W.; SCHIENKE, E. & ZHANG, Z., 2008: Land surface temperature variation and major factors in Beijing, China. Photogramm Eng Rem S **74** (4), 451–461.

YAN, W.; SHAKER, A. & EL-ASHMAWY, N., 2015: Urban land cover classification using airborne LiDAR data: A review. Remote Sens Environ **158**, 295–310.

YU, B.; LIU, H.; WU, J.; HU, Y. & ZHANG, L., 2010: Automated derivation of urban building density information using airborne LiDAR data and object-based method. Landscape Urban Plan **98** (3–4), 210–219.

YUAN, F. & BAUER, M., 2007: Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. Remote Sens Environ **106** (3), 375–386.

ZHANG, Y.; ODEH, I. & HAN, C., 2009: Bi-temporal characterization of land surface temperature in relation to impervious surface area, NDVI and NDBI, using a sub-pixel image analysis. Int J Appl Earth Obs **11** (4), 256–264.