Journal of Cleaner Production 238 (2019) 117858

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Spatial patterns of urban green infrastructure for equity: A novel exploration

Jingxia Wang [a, b, *], Chao Xu [c, d], Stephan Pauleit [b], Annegret Kindler [a], Ellen Banzhaf [a]

[a] UFZ - Helmholtz Centre for Environmental Research, Department Urban and Environmental Sociology, Permoserstraße 15, 04318, Leipzig, Germany
[b] Technical University of Munich, TUM School of Life Sciences, Chair for Strategic Landscape Planning and Management, Emil-Ramann-Str. 6, 85354, Freising, Germany
[c] Research Center for Eco-Environmental Engineering, Dongguan University of Technology, Daxue Road 1, 523808, Dongguan, China
[d] Institute of Geography, Humboldt University of Berlin, Rudower Chaussee 16, 12489, Berlin, Germany

ARTICLE INFO

Article history:
Received 25 April 2019
Received in revised form
28 July 2019
Accepted 31 July 2019
Available online 31 July 2019

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Urban ecology
Connectivity
Green spaces
Sustainable development
Urban structure types
Morphological spatial patterns

ABSTRACT

Urbanization processes spur the need for urban green infrastructure (GI) to support the well-being of urban dwellers and underpin a sustainable planning strategy. It is a challenge for urban planning to make cities equitable in a socio-spatial way for which strategic planning are demanded based on measured gradients of spatial equity for GI. Strategically, urban GI planning should pay tribute to the inherent spatial patterns and foster a fair distribution of GI towards spatial equity. Our aim is hence to investigate the spatial patterns of urban GI and disclose how spatial patterns affect spatial equity of GI in typical residential areas. The sample sites are in a central European city, Leipzig, the fastest growing city in Germany at present, with high pressure on urban growth. To elaborate an innovative approach, this study draws up a cascade of three methodological stages: 1) deploy the approach of an urban Morphological Spatial Pattern Analysis (MSPA) to compare urban GI patterns in three typical residential local districts, 2) use the GI-adapted Gini coefficient to measure spatial equity of GI distributions, and 3) explore the relationships between GI spatial patterns and spatial equity of GI for each residential type. In the context of three typical residential areas in Leipzig (i.e. (semi-)detached houses, linear multistorey housing estates, and perimeter blocks), a combination of the MSPA and a spatial equity measurement assists our novel exploration to disclose the relationships between the spatial patterns and the equity of GI distributions. Thus, we can prove strong similarities on the characteristics of spatial patterns in each residential type and observe a tendency of increasing equity from (semi-)detached houses to linear housing and further to perimeter blocks. As significant findings for the support of strategic urban GI planning, we discover that GI cores provide a restricted increase of spatial equity that limited to the lack of space. Furthermore, we suggest more GI bridges to enhance structural connectivity as well as spatial equity. This paper depicts the spatial equity of GI distributions in typical residential areas from morphological perspective, and thus further underpins urban GI planning for strategic networks as a key principle of the urban GI concept.

1. Introduction

Rapid urbanization has motivated the development of urban Green Infrastructure (GI) as a planning strategy to support the well-being of urban dwellers (Coutts and Hahn, 2015; Tzoulas et al., 2007). Urban GI has evolved since its inception in the mid-1990s (Firehock, 2010; Pauleit et al., 2011) and has been defined as the strategically planned and managed networks of natural and semi-natural lands, features and green spaces, and terrestrial, fresh-water, coastal and marine areas in urban areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and provides associated benefits to human populations (Benedict and McMahon, 2006; European Commission (EC), 2012, 2016; Naumann et al., 2011). As for the man-made infrastructure, which is also known as “gray infrastructure”, has been described as the functional support system of urbanized areas

* Corresponding author. Technical University of Munich, TUM School of Life Sciences, Chair for Strategic Landscape Planning and Management, Emil-Ramann-Str. 6, 85354, Freising, Germany.
E-mail addresses: jingxia.wang@ufz.de, jingxia.wang@tum.de (J. Wang).

https://doi.org/10.1016/j.jclepro.2019.117858
0959-6526/

(Wang and Banzhaf, 2018). Urban GI planning can be defined as “a strategic planning approach that aims at developing networks of green and blue spaces in urban areas that are designed and managed to deliver a wide range of ecosystem services” (EC, 2013; Maes et al., 2019). Planning for the connectivity and multifunctionality of urban green and blue spaces are inherent principles in this definition (Pauleit et al., 2018). Moreover, it has been suggested that urban GI should strive to integrate green with gray infrastructures, e.g. for sustainable storm water management, and be developed in a socially inclusive process to involve all relevant stakeholders. This has spurred an agreement that urban ecology (Marcus and Colding, 2014; Samuelsson et al., 2018), as a lens (Colding and Barthel, 2017), must be used to reflect and highlight the multiple ecosystem services (ESS) (Samuelsson et al., 2019) provided by urban GI. Among the multiple objectives GI has (EC, 2013) are the promotion of biodiversity, climate change adaptation, the provision of recreational spaces for citizens and supporting the shift towards a green economy (Pauleit et al., 2018).

Urban GI planning should also strive to achieve a relatively equal socio-ecological development (Pincetl and Gearin, 2013) by balancing disparities in the distribution of GI (Kabisch and Haase, 2014) and its ESS. Spatial equity of GI distributions is crucial for individual urban inhabitants for having the same distance to access services (Heckert and Rosan, 2016). It implies that spatial analyses on the distance of citizens to urban GI, such as at cognitive level, where people in the street experience urban green spaces (Colding and Barthel, 2017; Marcus and Colding, 2014), and at eye level (Samuelsson et al., 2019) or at site level (Rall et al., 2019) where urban dwellers may participate into the strategic planning, may shed new light on the connectivity (Samuelsson et al., 2019) and configuration of urban GI. Allocation of GI is influenced by the character of gray infrastructure, namely amount, density and configuration of the built-up structures (Marcus and Colding, 2014), roads, and any other paved surfaces (Wang and Banzhaf, 2018). Therefore, the spatial distribution and the character of different urban morphology types such as residential areas, commercial and industrial zones (Gill et al., 2008; Pauleit and Duhme, 2000), determine the quantity and quality of urban GI (Romero et al., 2012; Van der Zanden et al., 2013). Consequently, urban GI planning will benefit from the analysis of the spatial patterns of GI to reveal the intertwined relationships between GI and built-up structures (Pauleit and Duhme, 2000; Wickop et al., 1998). However, studies concentrating on the spatial patterns of urban GI are still rare (Alberti and Marzluff, 2004; Holt et al., 2015), especially in residential areas, even though they are meaningful for urban GI planning.

Evidence has emerged to support the claim that spatial patterns of built-up structures are influencing the ecological functional connectivity (Saura et al., 2011; Vogt et al., 2007, 2009; Wickham et al., 2010) and thereby the provision and functioning of GI (Alberti, 2005; Bierwagen, 2005; Cavan et al., 2014; Tratalos et al., 2007; Whitford et al., 2001). It necessitates more and in-depth studies concerning spatial patterns and their effects on biodiversity and urban ESS (Alberti, 2005). The supply of urban ESS, as Samuelsson et al. claimed (2018; 2019), is influenced by the urban form as well as the spatial patterns of urban areas. To describe the spatial patterns, various methods and tools have been developed and applied in urban ecology (e.g., McGarigal and Marks (1995); Kim and Pauleit (2007); Kuttner et al. (2013)) to reveal the links between urban GI patterns with ecological and social functions (Luck and Wu, 2002). They comprise methods such as Fragstats (Luck and Wu, 2002; McGarigal et al., 2002; McGarigal and Marks, 1995), which provides a series of landscape metrics (e.g. area/density, patch shape index and proximity metrics) to detect the urbanization gradient of landscape patterns (Kupfer, 2012; Luck and Wu, 2002) and biodiversity conservation (Kim and Pauleit, 2007), and tools like least cost measures (Sutcliffe et al., 2003) as well as genetic patterns that offer a more ecologically oriented approach to quantifying spatial patterns (e.g., Chardon et al. (2003); Coulon et al. (2004); Hokit et al. (2010)). Other graph-based approaches are also applied, for instance, the Conefor Sensinode tool (Saura and Torne, 2009) quantifying habitat patches for connectivity by calculating nodes, links, and graph-based metrics, including the number of links, number of components, integral index of connectivity and so forth; or the Circuitscape tool (McRae and Shah, 2009) which could calculate and map measures of resistance, conductance, current flows, and voltage. These approaches are widely utilized to analyze the structural landscape metrics and connectivity, but they are all rooted in graph, network, and circuit theory (Kupfer, 2012), and being limited by inconsistent evaluation results from human interpretation (Ostapowicz et al., 2008). Their definitions of thresholds such as patch width are in terms of selected contexts. With regard to methods that analyze spatial patterns, the former (i.e. structural indices of patch shape such as perimeter to area ratio) and the latter (i.e. graph-based approaches) can explore the importance of corridors as connectors between nodes (Ostapowicz et al., 2008) in a network, but only after these corridors have been defined elsewhere.

The Morphological Spatial Pattern Analysis (MSPA) approach developed by Vogt et al. (2006) and Soille and Vogt (2009) has been an evolution apart from the aforementioned methods, because it can map corridors as structural links between core patches and this feature cannot be achieved with any other methodologies (Kupfer, 2012) (i.e. neither landscape metrics (structural indices) nor graph-based approaches). Indeed, MSPA is a mathematical morphological algorithm that performs a segmentation analysis of the foreground objects against the background matrix (ibid.) as well as a tool to describe spatial patterns and connectivity of urban GI (Ramos-Gonzalez, 2014). MSPA makes pattern analyses more interpretable by incorporating visualization maps, classifying and mapping individual pixels into different categories, such as core, bridge, loop, branch, perforation and edge (Barbati et al., 2013). Therefore, the MSPA offers an effective approach to investigate GI in heterogeneous urban areas, allowing to identify and quantify the spatial patterns of GI (Nielsen et al., 2016) and distinguish between them (e.g. bridges as connectivity for species dispersal and movement) (Barbati et al., 2013). Up to date, MSPA approach has been used primarily in forest areas (Goetz et al., 2009; Riitters, 2011) to detect forest connectors (Saura et al., 2011), monitor forest composition and configuration (Ostapowicz et al., 2008) in ecological restoration areas for site prioritization (Wickham et al., 2017), or in riparian zones to identify the structural riparian corridors for conservation and management purposes (Clerici and Vogt, 2013). However, there are few studies that have been performed in urban areas (Ramos-Gonzalez, 2014), and in this paper the MSPA is applied in the residential areas for the very first time.

In this study, we aim to use the MSPA approach to shed light on the relationships between the distribution and the connectivity of urban GI and built-up structures in typical residential areas of a central European city for the analysis of spatial equity and functionality of urban GI. It is hypothesized that residential areas show diverging morphological spatial patterns of GI and simultaneously result in uneven GI distributions and connectivity (e.g. species dispersal and movement). Aside from exploring urban GI spatial patterns for equity in typical residential areas, our specific objectives are: 1) to compare urban GI morphological spatial patterns in different types of residential areas, 2) to analyze spatial equity of GI using GI-adapted Gini coefficient, 3) to investigate the relationships between GI's spatial patterns and Gini coefficient in distinct residential types.

2. Methodology

2.1. City of Leipzig, Germany, and its sample sites

Our study deals with the city of Leipzig, Germany. Leipzig is located in the north-western part of Saxony and covers an area of 297 km^2 (Fig. 1). With 596,517 inhabitants in 2018, it is the largest city in Saxony with a population density of 2008 inhabitants per km^2. One of the most well-preserved alluvial forests in Europe traverses Leipzig. From south to north and then towards the northwest, the forest stretches through the urbanized area, serving as the green lung of the city. This is one of the main reasons why it is one of Germany's greenest cities with an average of 254 m^2 vegetation cover per inhabitant (Maes et al., 2019; Stadt Leipzig, 2003, 2018). Another notable phenomenon of GI is the high share of public community garden allotments (approx. 1240 ha) (Stadt Leipzig, 2018) which provides additional recreational space for thousands of residents and has a positive influence on the local climate (Cabral et al., 2017).

During the last decade Leipzig has become the fastest growing city in Germany with considerable increase in economy and cultural diversity. Moreover, Leipzig prides itself with its eagerness in sustainable urban development (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), 2007; Stadt

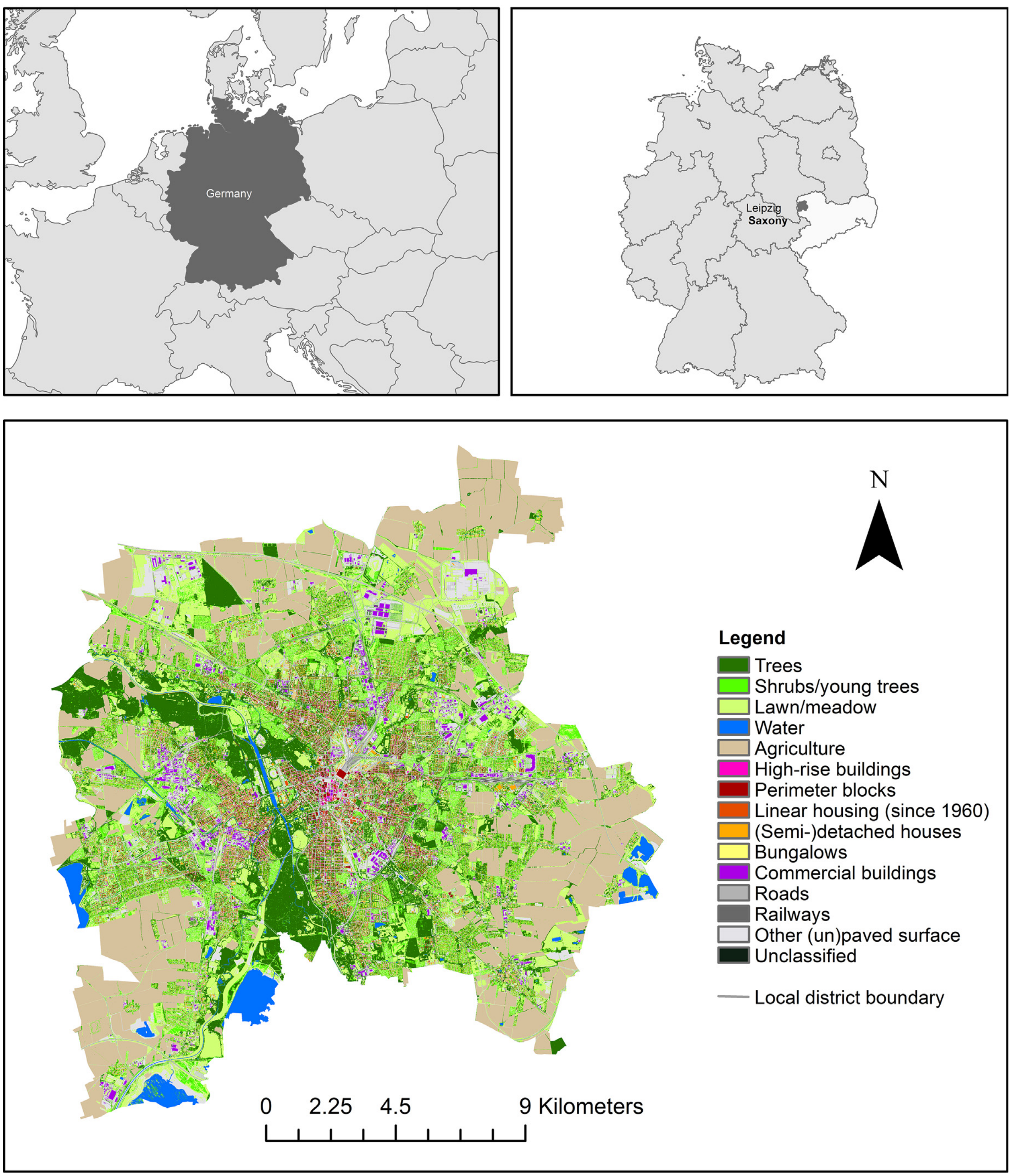


Fig. 1. Location of the case study: (a) Germany in Europe, (b) Leipzig in Germany, (c) The City of Leipzig, 2012.

Leipzig, 2019). As part of these efforts, urban planning makes major endeavors in re-densifying the municipal space thereby preventing urban sprawl. As a consequence, land development processes have been leading to a competition between GI and housing including public infrastructure (Fig. 1). Grounded on a high recognition for maintaining or even enhancing urban ecosystems and their services by fostering local GI, the city council has developed a GI quality concept, the so-called Masterplan Green Leipzig (2030) (Stadt Leipzig, 2018). Nonetheless, the increasing population numbers and density provoke high leverage. The need for providing schools, kindergartens, local amenities and new dwellings for residents is a strong driver shaping the character of urban compaction. Maintaining a green city that secures a high environmental quality of urban life and offering housing and public infrastructure are currently the major challenges for urban planning. At present, the creation of a new urban development concept for Leipzig is on its way (Integrated urban development concept (INSEK) Leipzig 2030; Stadt Leipzig, 2018) where information such as the one generated in this study is needed.

The structure of the built-up area in Leipzig is characterized by three major types of residential buildings (Fig. 2): perimeter blocks (Wilhelminian-style buildings) with 5–6 storey high buildings in a block alignment with an interior courtyard, linear multistorey housing (mainly prefabricated slab buildings) of mostly 6-16 storey high buildings with common spaces in-between, and 1-2 storey, (semi-)detached houses (single and duplex houses) with gardens. Being a fairly homogeneous city (Figs. 2 and 3), many of the 63 local districts can be assigned to one of these dominant types. The city has one of the highest proportion of Wilhelminian-style residential buildings (Gründerzeitbebauung) in Germany. The construction of these buildings began during the reign of King Wilhelm II after 1850 and continued until 1914. Much later, during the era of the German Democratic Republic, one of the country's largest prefabricated slab building complexes were built in Leipzig. They became home to more than 80,000 residents in the 1980s (Banzhaf et al., 2018). The construction of single and semi-detached (or duplex) family houses started in the 20th century in large designated settlement areas and is continued up to date, albeit rather patchy and dispersed throughout the city.

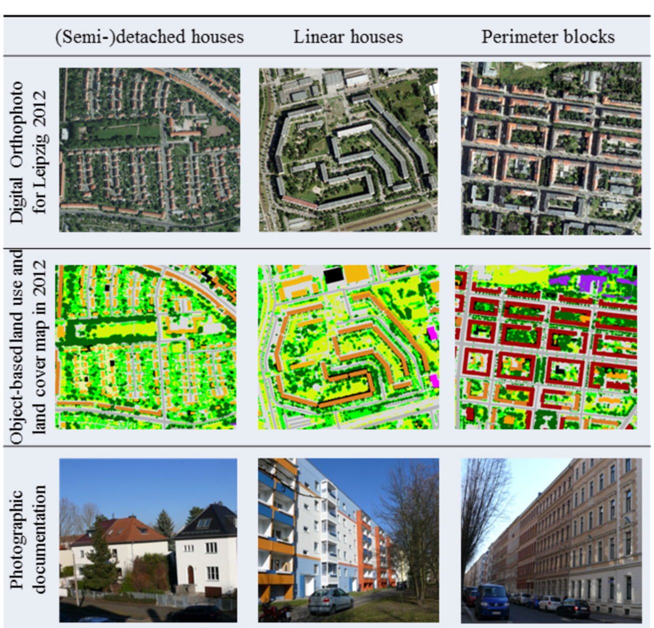


Fig. 2. Digital orthophotos (DOP) (2012), corresponding object-based land use and land cover map, and photographic documentation for each of the dominant urban structure types. Sources: DOP by Ordnance Survey, state of Saxony, Germany; map own calculations, photography by E. Banzhaf.

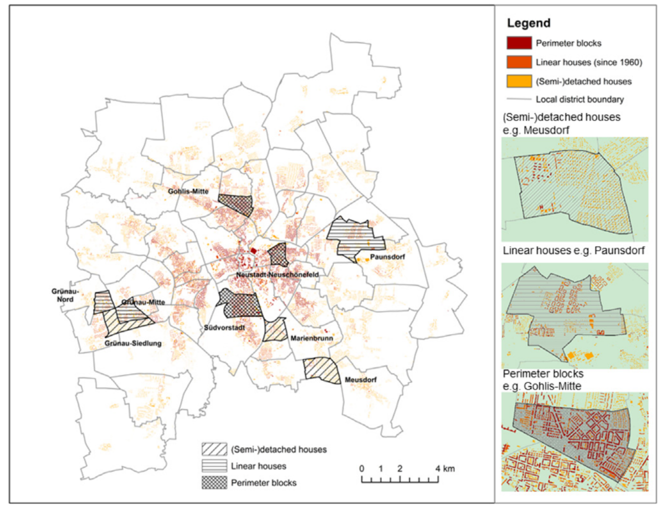


Fig. 3. Location of the nine sample sites especially highlighted in the City of Leipzig with its 63 local districts.

We applied and tested our method for selected sample districts (Fig. 3) considered as fairly representative for the three residential types. For an even urban coverage, we selected three sample districts each: typical local districts for the Wilhelminian-style perimeter blocks are Gohlis-Mitte in the north, Neustadt-Neuschönefeld in the central east, and Südvorstadt in the south, constructed during the first period of spatial expansion (mainly around the turn of the 19th century). Linear multistorey housing estates are rather large and located towards the fringe of the urban area. As Grünau was one of the largest linear housing estates in the former German Democratic Republic (GDR), being constructed in the 1970s and 1980s; thus, we chose two local districts from this vast area in the southwestern part of the city (i.e. Grünau Mitte and Grünau Nord), and Paunsdorf as the third sample district in the eastern part. With respect to the typical urban structure of (semi-)detached houses we decided to exclude the most recent areas under development due to patchiness and present lack of GI. Instead, we chose three residential areas Grünau-Siedlung in the west, Marienbrunn in the central south and Meusdorf at the southeastern outskirts of Leipzig that were built between the 1920s and 1930s. All the selected nine districts have a stable and long history of developments for which their respective municipal boundaries are stable before/after German reunification (Kabisch et al., 2018). Our selection did not include the local districts that were incorporated into the City of Leipzig between 1993 and 2000 as a municipal area reform, concerning they have a more rural character. The principles of our selection are, in essence, the historical urban developments (Kabisch et al., 2018), the fairly representative (Banzhaf et al., 2018), and the high population densities for the year 2012 in the City of Leipzig (Stadt Leipzig, 2012), for the purpose of underpinning our aim of exploring the green spaces mostly used.

2.2. Data collection — spatial data and materials

To gain spatial information on the urban land use and land cover, we employed digital orthophotos (DOP), a digital elevation model (DEM) and a digital surface model (DSM) at very high resolution. These datasets were processed in an object-based image analysis (OBIA) approach described by Banzhaf et al. (2018), in which different datasets were all rescaled to 1 m ground resolution for the year 2012. The advantage of this dataset is not only its scale but also its three-dimensional classification scheme and refined categories. The categories comprise urban built and green structures including green cover types such as trees, shrubs/young trees, lawn/meadow, agriculture and water giving information on the typical residential areas explained in a previous study (Banzhaf et al., 2018). Therefore, the object-based classification facilitates our research from two aspects: first, to analyze the morphological patterns of GI at a very high spatial resolution, and second, to extract typical residential areas for the analysis of GI towards equity and connectivity. In terms of statistical records on demographic data, we included all urban populations with first and second places of residency living in Leipzig. By also considering those with a second residency we paid tribute to international students, commuters, and those who contribute to a realistic picture of the urban dwellers and who use GI.

2.3. Spatial pattern analysis method

The morphological spatial pattern analysis (MSPA) was first introduced by Matheron et al. in 1967 (Matheron, 1967) and then enhanced by Soille (2013). It has been further applied in landscape ecology in depth by Vogt et al. since 2006 (Soille and Vogt, 2009; Vogt and Riitters, 2017; Vogt et al., 2007). This approach has so far been applied to classify spatial patterns, as well as to map functional networks (Vogt et al., 2009; Wickham et al., 2010) and landscape corridors (Clerici and Vogt, 2013; Vogt et al., 2007). Since then, the MSPA has continued to be developed for landscape ecological studies. In this paper we used the latest GuidosToolbox 2.8 to conduct our GI morphological mapping. This toolbox was recently updated by the Joint Research Centre of the European Commission. Preprocessing steps comprised the reclassification of spatial data into a binary map using ArcGIS 10.6 compared to Soille and Vogt (2009) and Wickham et al. (2017), which included GI and built-up structures to match our research focus, namely the spatial patterns of GI.

In order to explore urban GI patterns applying MSPA (Vogt and Riitters, 2017), we defined the primary green cover types (Davies et al., 2015) that are available from our spatial data source as our foreground (primary targets) map, and simultaneously set other built-up structures as our background map. From the classified dataset we selected trees, shrubs/young trees, lawn/meadow, agriculture, and water as our five focal classes for the mapping of the GI morphological patterns, setting all other built-up structures, including railways, paved surfaces, commercial buildings etc., to the background. These GI categories reflect all primary GI types in the City of Leipzig providing ESS in urban areas. When carrying out the spatial pattern analysis we were in line with the methodology by Wickham et al. (2010). Although a ready-made MSPA toolbox was available, we decided to customize ours according to our sophisticated research focus and our much more refined input data. For this reason we undertook preprocessing steps like tiling to have all data tailored for further processing. Preprocessing comprised i) cutting buffered sub-tiles, ii) processing buffered sub-tiles for MSPA, and iii) resampling the final image to comply with the prerequisites for our MSPA investigation and at the same time support our aim to keep our high resolution dataset at the spatial resolution of 1 m; otherwise there are potential risks of losing information due to the change of spatial resolution, because without aforementioned preprocessing, our input data are restricted to a square map of 10000 * 10000 pixels for the MSPA processing (Vogt and Riitters, 2017). As the second step, we set the connectivity as eight-neighbor to analyze each pixel being surrounded by different pixels in eight directions.

According to our customized method in Section 2.3, our adapted MSPA resulted in seven classes of GI spatial patterns. They are named core, bridge, loop, branch, edge, perforation and islet. These classes reflect the spatial heterogeneity of GI in the residential areas. Instead of overlying several maps in geographic information system software, our method from Soille and Vogt (2009) was based on concepts from mathematical morphology (Soille, 2003). The MSPA classes are defined in Table 1.

2.4. Data processing for the calculation of the GI-adapted Gini coefficient

Traditionally, Gini coefficient has been employed in economics as a valid index to measure the income inequality of inhabitants. However, a growing number of references (Kabisch and Haase, 2014; Li et al., 2017; Wüstemann et al., 2017; Xu et al., 2018) more recently demonstrate that it can be expanded to an effective index to assess sustainable urban development as well as the provision of cultural ecosystem services (Kabisch and Haase, 2014; Li et al., 2009). In these cases, the supply of the nearby GI is regarded to be more beneficial for residents in terms of daily short-term recreational services (Xu et al., 2018), for which the maximum distance from the residence locations to nearby GI should not be further than 300 m (Kabisch et al., 2016; Lauf et al., 2014), and the minimum size of GI patch should cover approximately 2 ha (Handley et al., 2003; Lauf et al., 2014).

A newly adapted index will foster our analysis to point to environmental equity in a spatially explicit way (i.e. the GI-adapted Gini coefficient). We used this index, which is expressed as follows, to measure the spatial equity of the GI distribution in local districts with different dominant residential types.

$$G = 1 - \sum_{i=1}^{n} \frac{P_i}{P}(B_{i-1} + B_i) \tag{1}$$

where P is the total population of the local district; P_i is the population number of the grid cell *i;* and B is the cumulative share of GI

Table 1
Classification of the morphological spatial patterns.

MSPA classes	Definitions
Core	GI surrounded by all sides (8-connectivity) by GI and greater than 3 m distance from built-up areas
Bridge	GI that connects two or more disjunctive areas of GI cores
Loop	GI that connects an area of GI core to itself
Branch	GI that extends from one area of core, but does not connect to another area of core
Perforation	Transition zone between the GI and built-up areas for the interior regions of GI, and has the shape of a doughnut in which a group of GI types is shaped by the perforations (inner edges).
Edge	Transition zone between GI and built-up areas
Islet	Unconnected class without core.

in a 300 m buffer around grid cell *i*. The GI-adapted Gini coefficient ranges from 0 to 1, with 0 representing total equity, and 1 indicating absolute inequity.

The GI-adapted Gini coefficient was calculated according to the following steps: first, GI patches were selected with a minimum size of 2 ha, and the population density for the residential areas in each local district was computed, dividing the population number of the respective local district by the total residential areas within the boundary of the local district; second, each sample local district was intersected with a 100 m $\times$ 100 m grid file in ArcGIS 10.6, and the grids with their centroids located in each sample district were collected; third, for each sample local district, the population number within each grid cell and the area of GI (selected in the first step) within a 300 m buffer around the centroid of the grid cell were calculated. Grid cells with less than two residents were omitted from further mathematical processes, and the GI-adapted Gini coefficient was quantified for all sample local districts.

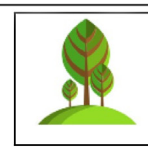
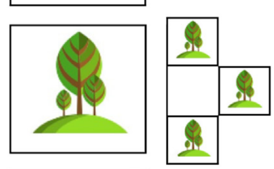
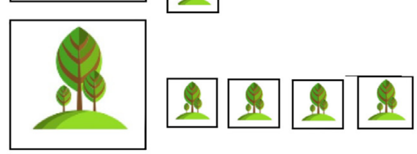
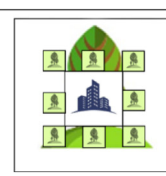
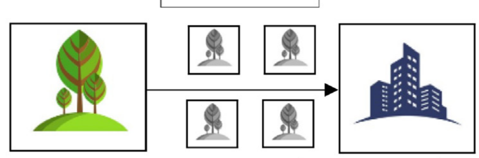
3. Results

3.1. Morphological spatial pattern analysis for typical residential areas

3.1.1. Delineation and interpretation of morphological spatial patterns

Our developed MSPA resulted in seven classes with specific geometric features. This prerequisite enabled us to define and analyze our classes in depth according to our research aim and the underlying Land Use and Land Cover (LULC) classes to understand the structural connectivity of GI. As one significant result, we characterized each class in Table 1 as different GI patterns in terms of the GI concept by Wang and Banzhaf (2018), through which we were able to better understand their relationships in our local sample districts. As Table 2 shows, MSPA classes may either belong to *GI exclusively* (pure GI patterns) or they may be part of the *GI*

Table 2
Conversion of the MSPA classes into structure classes

MSPA classes	Structure classes	Illustrations
GI exclusively		
GI core	GI core	
GI bridge	External connectivity 1: GI core areas to other different GI core areas	
GI loop	Internal connectivity 1: GI core areas to the same GI core	
GI branch	Partial (half) connectivity	
GI connected to built-up areas		
GI perforation	Internal connectivity 2: transition zone between GI to built-up areas for interior regions of GI cores.	
GI edge	External connectivity 2: transition zone between GI and built-up areas.	
GI islet	Unconnected	

connected to built-up areas. The *GI exclusively* classes encompass GI core, bridge, loop and branch. As for the *GI connected to built-up areas*, they enclose GI perforation, edge and islet. They all contribute to structural connectivity at different extents.

The GI core in Table 2 is usually composed of a broad spectrum of types of green and GI elements, encompassing the currently primary functioning GI. Other GI spatial patterns such as bridge, loop, and branch, however, are classified in terms of their relationships with surrounding GI core. As one significant result, we converse MSPA classes into seven different structural classes and they reflect different intensities of structural connectivity (Table 2). GI bridges (Fig. 4) that connect to the different GI cores are significant corridors for providing favorable habitat and paths from one core to another. GI loops represent shortcuts connecting spaces of a core area to itself. In general, both the bridges and loops indicate functional pathways, in which maintenance is crucial to sustain any transfer of individuals between the same or different GI cores. Branches might be developed from bridges and loops, and further recognitions of locations of branches and bridges would then provide notices where there might be vulnerable GI corridors. Perforations and edges are both transition zones between GI cores and the built-up area.

3.1.2. Comparison of the GI morphological spatial patterns in different types of residential areas

The GI spatial patterns of all sample local districts were extracted and the results for our nine samples are illustrated in Fig. 5. Each of the three local districts dominated by (semi-)detached houses has similar structures/distributions of morphological spatial patterns. From high to low, the orders of proportions of the top five spatial patterns are the same in proportions (i.e. GI core > GI bridge > GI edge > GI loop > GI branch). There are relatively high fractions of GI core areas at all of the three cases, i.e. Grünau-Siedlung, Marienbrunn, and Meusdorf, which reflect a relatively high level of pure GI coverage. With respect to the GI bridges and GI edges, these two patterns accounted for almost the same percentage. As a result, the probabilities between external connectivity 1 (GI core areas connected to another different GI core area) and external connectivity 2 (GI cores to built-up areas) were nearly the same. The respective proportions of the overall spatial patterns were quite similar from GI core to islet.

As for the local districts prevailing linear multistorey housing estates, it shows similarities in the distributions of GI morphological patterns as well. From high to low, the orders of proportions of the first five spatial patterns are consistent, i.e. GI core > GI edge > GI bridge > GI branch > GI loop. For this residential type, it is interesting to note that the proportions of GI bridge are almost half of the GI edge patterns connected to the other built-up areas. This result explains that GI in districts dominated by linear multistorey housing frequently reaches right up to typical building structures rather than to other GI cores. It reveals potential limits of GI connectivity in these sample districts for the reason that GI edges (external connectivity 2) have less structural connectivity compared to GI bridges (external connectivity 1) according to Table 2.

At those local districts dominated by perimeter blocks which contain mostly Wilhelminian-style buildings, i.e. the typical residential districts of Gohlis-Mitte, Neustadt-Neuschönefeld, and Südvorstadt, it is notable that the fractions of GI cores and GI islets are the highest compared to the aforementioned two sample districts. However, compared to the districts dominated by linear multistorey housing types, the GI bridges are apparently much less than half of GI edge patterns. During that era of urban expansion, an extremely high pressure was put on urban dwellings because of the strong growth of cities undergoing industrialization (mainly second part of the 19th century). Therefore, two contrasting urban structures were created in those days that still predominant the urban character of Leipzig (i.e. Wilhelminian-style perimeter blocks in the block alignment (some of them with interior yards), but hardly any GI in streets, and few large areas with allotment gardens that met the dwellers' need for green space).

As one significant MSPA result, each of the three typical residential areas has its own spatial GI patterns, while within the same type of residential districts, the GI patterns are similar. The section that follows will explore how these characteristic patterns influence the equity of GI in residential areas.

3.2. GI-adapted Gini coefficient

To know the spatial equity of GI distributions, we chose the GI-adapted Gini coefficient index. In our nine sample local districts (Fig. 6), the Gini coefficient ranges from 0.096 to 0.463, representing large differences of GI distributions from even to comparatively uneven, given that the smaller Gini coefficient indicates a

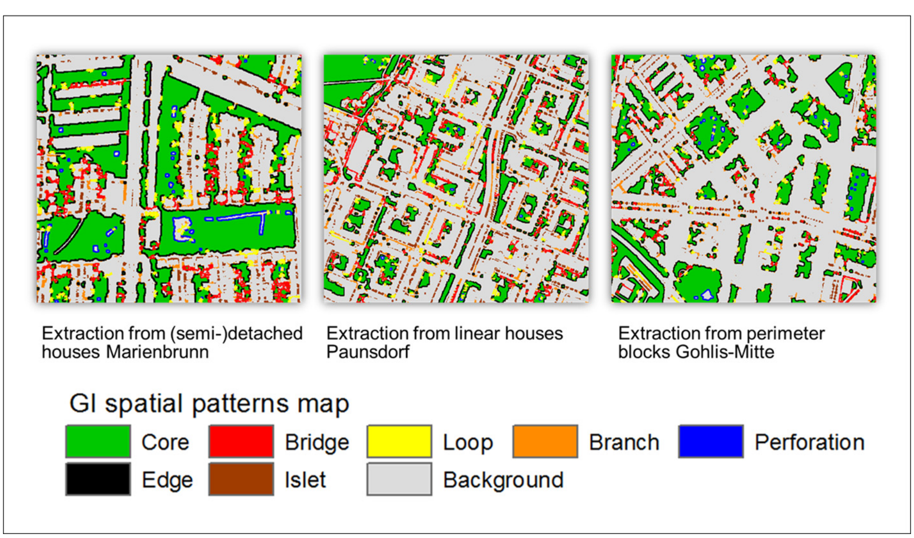


Fig. 4. Extractions from GI spatial patterns map in three types of residential areas.

higher equity of potential access to the same amount of GI and vice versa.

The overall Gini coefficient of each exemplified residential district was evaluated as well. As dash lines in Fig. 6 show, the spatial equity of GI distributions varies with reference to the existing type of residential areas. Despite the small variations of the Gini coefficient among different local districts, there is an apparent tendency that the GI coefficient strikingly increases from samples with (semi-)detached houses to linear multistorey housing districts, and shows the highest rates at local districts with perimeter blocks. It means that GI distributions in the districts predominated by perimeter blocks are the most unequal, while those local districts with (semi-)detached houses show the most equal distribution of GI.

Compared to those local districts dominated by linear multistorey housing and perimeter blocks, the GI distributions of the local districts with (semi-)detached houses are relatively even. More strikingly, GI availability is most uneven in local districts with perimeter blocks, even though there are interior courtyards in some blocks of these historical building complexes. Consequently, the residents in such typical residential districts (e.g. Neustadt-Neuschönefeld, Gohlis-Mitte, or Südvorstadt) probably have the lowest equity to accessing the same amount of GI. Evidently, those local districts with prevailing (semi-)detached houses have a higher spatial equity of GI distributions. Beyond, their residents can much easily access the nearby GI for further recreation.

3.3. Relationships between GI spatial patterns and Gini coefficient in the residential types

The spatial patterns of each type are different (Fig. 7), even though the GI core accounts for the biggest fractions among all the three different structural areas. As a significant result, we observed positive correlations between GI bridge and edge patterns with the spatial equity of GI distributions in (semi-)detached housing areas. In these areas a large number of GI bridges and edges connect to other GI cores and sealed surfaces respectively, and the GI distributions usually show more equity in these predominant local districts.

For the same type of building structures, the spatial patterns of GI are rather similar as Figs. 5 and 7 show. For instance, the proportions of both bridge and edge for the local districts dominated by (semi-)detached houses are quite similar. Therefore, the GI cores are relatively well connected, while the findings also imply potential vulnerability of GI because the edge is usually a transition zone between GI and built-up areas. The differences in the proportion of edge and bridge areas in (semi-)detached dominated local districts are small, whereas those in the local districts dominated by linear multistorey housing and perimeter blocks are larger. Particularly for the latter, the results suggest a limited connectivity between GI core areas. Overall, it appears that GI cores alone cannot firmly ascertain a high level of spatial equity as the Gini coefficients indicate.

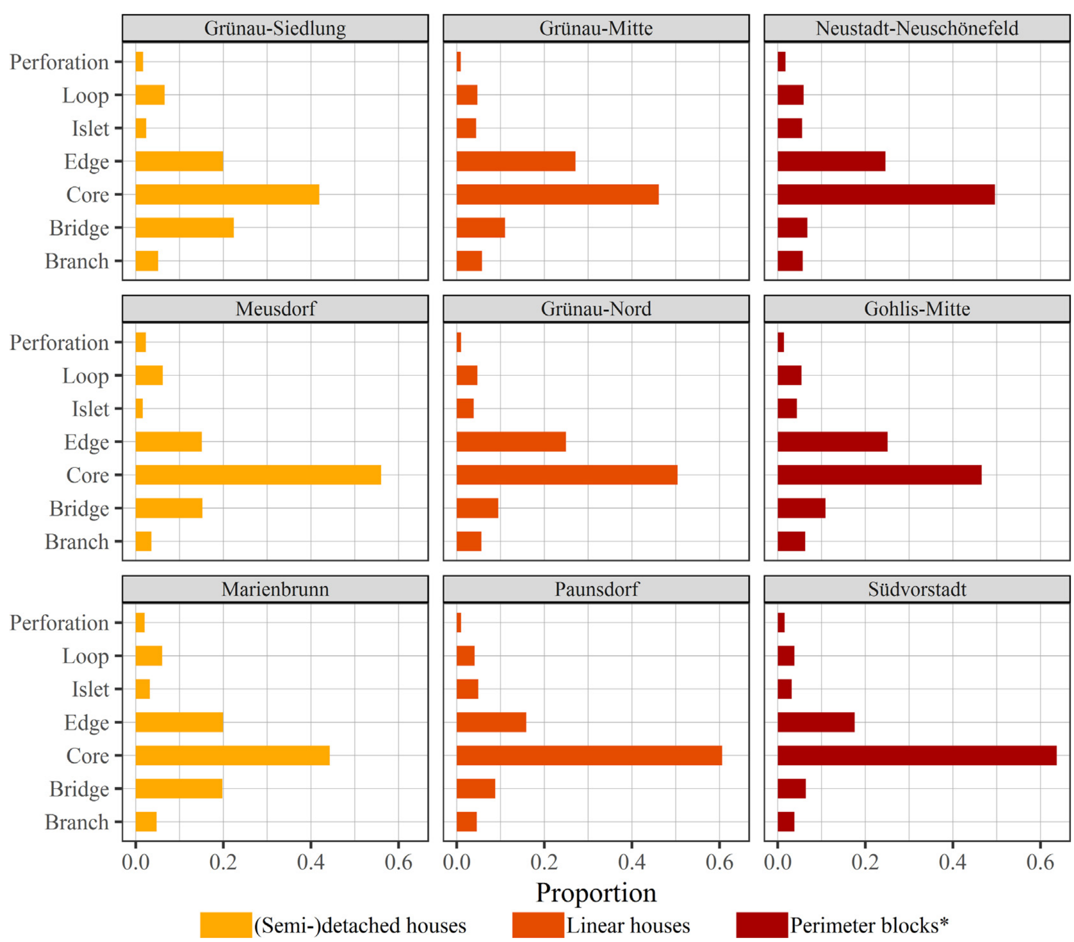


Fig. 5. MSPA of nine local districts, three dominated each by (semi-)detached houses, linear multistorey housing and perimeter blocks respectively (* mostly Wilhelminian-style buildings from 1850 to 1914).

4. Discussion

We analyzed the spatial patterns in the local districts representing the three dominant types of residential areas in Leipzig, Germany. The typical urban structure comprises (semi-)detached houses, linear multistorey housing estates and perimeter blocks. In this paper, the underlying hypothesis — local districts with respective predominant residential structure types that underlie diverging morphological spatial patterns of GI, and which may result in uneven GI equity — is attributed to the combination of morphological spatial pattern analysis with an index that measures spatial equity to verify this assumption.

Our analysis provides a classification of seven GI feature classes (Table 1) and different structure classes (Table 2), covering multiple aspects of the GI spatial patterns of our sampled local districts and their structural connectivity. It enables us to discuss how these urban GI patterns affect the ecosystem functions respectively. GI cores containing GI types such as trees, shrubs/young trees, lawn/meadow, agriculture, and water can be significant habitats for species (Wickham et al., 2010) and represent the major ESS provisioning areas (Riitters, 2011). In our sample local districts, they are particularly important since they affect species habitat and resource availability. The core contains shrubs/trees that provide regulation services, e.g. cooling capacity (Goetz et al., 2009), lawn/meadow for recreational cultural services, for insect pollinator activities and movement paths (Vogt et al., 2007), agricultural areas serve for food provision services in urban areas and so forth. The bridge class characterizes the potential movement pathways (ibid.), not only for the native plant and animal species but also for residents. These spatial patterns are witnessed in our nine local test districts with a large number of urban dwellers. Bridges may be the vulnerable GI for future fragmentation and conversion to any built-up structures. Furthermore, they are primary networks for GI connectivity (Ahern, 2007, 2011) because they join two or more disjunctive areas of GI cores, such as stepping stones, which might be the primary movement paths for insects. Both loop and branch classes are connected to GI core. As for the perforation and edge, they are transition zones between GI and built-up structures. It seems that perforations are the inner edges and thus indicate higher structural connectivity to GI core. It is the very nature of an islet to be disjoint and usually too small to contain a core. Islets might be a small number of trees, shrubs/young trees surrounding any built-up structures like buildings and parking lots, or along streets, not large enough to be recognized as GI core areas, even though they reflect small and fragmented GI connected to any sealed surfaces. Native flora and fauna in isolated patterns such as islets usually decline as a result of habitat loss and interspecific interactions (Alberti and Marzluff, 2004), reduced connectivity (Alberti, 2005), and then a loss of biodiversity (Goetz et al., 2009; Wickham et al., 2017).

In comparing urban GI morphological spatial patterns in different types of residential areas, we discover that the single spatial pattern of GI in local districts with the same residential building structure show their own diverse configurations. However, a general tendency of similar distributions of morphological spatial patterns is observed for each type of residential areas, respectively

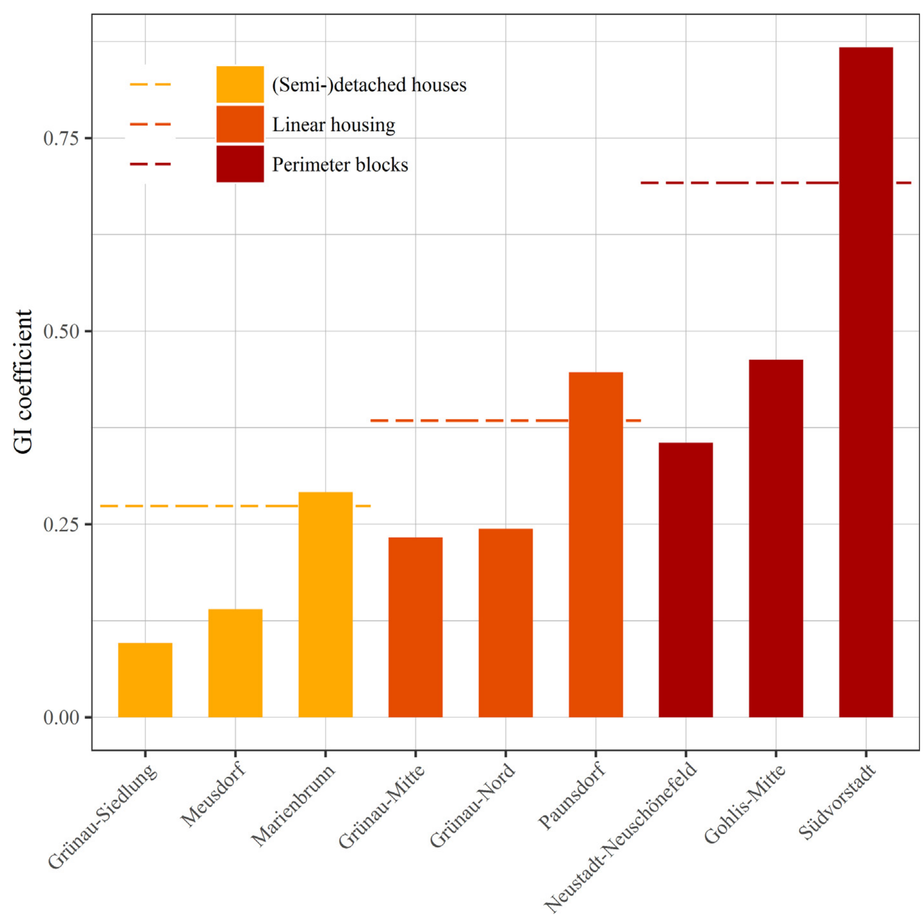


Fig. 6. The Gini coefficient of the nine sample local districts dominated by (semi-)detached houses (left), linear housing estates (center) and perimeter blocks (right); dash lines illustrate the Gini coefficient for each type of residential areas.

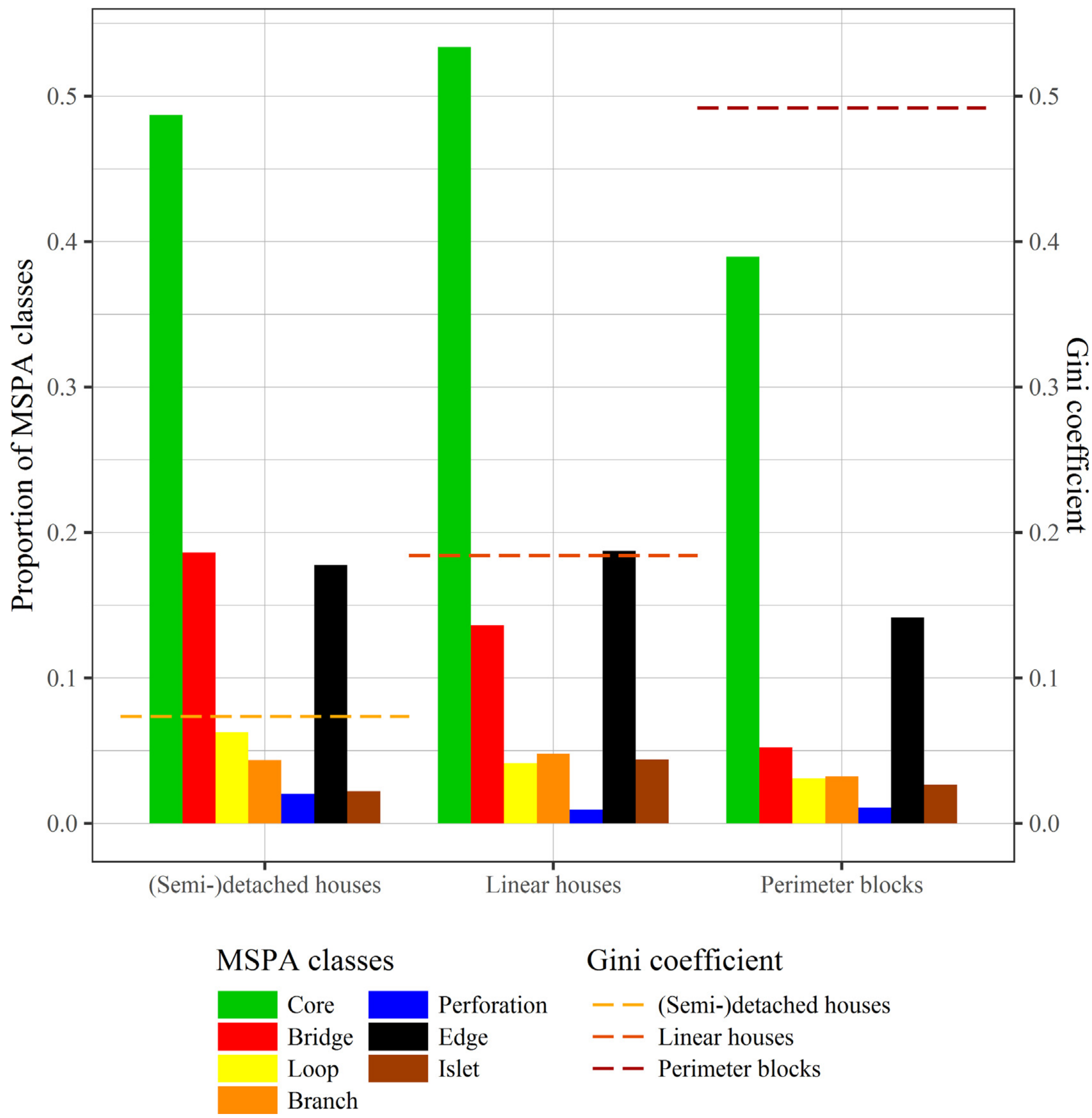


Fig. 7. GI-adapted Gini coefficient for three types of typical residential areas which are dominated by (semi-)detached houses, linear houses and perimeter blocks respectively; colors are in line with the general color scheme using MSPA).

predominated by (semi-)detached houses, linear multistorey houses and Wilhelminian-style perimeter blocks. In other words, all local districts where (semi-)detached houses are prevailing show almost the same proportions of GI feature class bridge and edge; as for local districts predominated by linear multistorey and perimeter blocks, their GI bridges decrease to less than half compared to the fractions of GI edges. Besides, when referring to the feature class loop, it represents a shortcut by directly connecting core areas. In our study, bridges made positive effects on the structural connectivity of GI, but their implications for the corresponding spatial equity of the GI distributions are still unclear. At present, we are not yet able to advise whether or not more loops are needed to provide the spatial distributions of GI more evenly.

We used Gini coefficient to analyze the spatial equity of GI. Regarding this spatial equity, a key finding is that local districts with prevailing (semi-)detached houses have a higher spatial equity of GI distributions. As a consequence, their residents can much easily access nearby GI for further recreation. This result is emphasized in so far as this structure type is socially dominated by middle-class residents (Banzhaf et al., 2018; Nuissl et al., 2005). The GI distributions are relatively unequal in districts prevailed by linear multistorey housing and perimeter blocks. In these residential areas, urban dwellers have a lower equity of potential access to the same amount of GI, compared to dwellers in districts predominated by (semi-)detached houses. This outcome 1) pictures the variations in the spatial equity of the GI distributions for different types of residential areas, and 2) reveals substantial impacts on potential recreation functions of GI.

Combined MSPA with spatial equity of GI serves to our novel exploration of the multiple relationships between spatial patterns and equity of GI distributions. In general, bridges that connect from one GI core to a different GI core have a significant influence not only on the GI structural connectivity (Clerici and Vogt, 2013) but also on the spatial equity of GI distributions. For each of the local sample districts, GI bridges and edges are the most important feature classes in support of the spatial equity of GI distributions, with a much higher impact than the GI core areas. GI bridges enhance the connectivity between GI cores and significantly increase equity on green spaces in linear multistorey housing estates, particularly in local districts with a relatively high Gini coefficient.

For instance, in Paunsdorf and Südvorstadt, the potentials of enlarging GI cores are limited to the lack of space. These findings clearly support strategic planning for networks as a main principle of the urban GI concept (e.g. Pauleit et al., 2017; Wang and Banzhaf, 2018). The strategies for better providing urban ESS need to consider 1) spatial patterns and morphology of residential areas, such as sharing long edges with green spaces such that many residents are close to them (Samuelsson et al., 2018), 2) the ecological connectivity of urban GI, so that both urban dwellers and the flora and fauna themselves could cognitively connect with the biosphere (Colding, 2007; Colding and Barthel, 2017).

Overall, the MSPA reveals considerable variations in the morphological spatial patterns of GI and the different levels of structural connectivity of GI across each of the typical residential areas. In the method used to calculate the Gini coefficient, we defined a 300 m buffer around residential areas. The 300 m threshold was quite influential to measure citizens' proximity to urban green spaces in many cities, such as Greater Manchester, UK (Kazmierczak et al., 2010), the City of Jeddah, Egypt (Khalil, 2014), and Shanghai, China (Fan et al., 2017). However, we cannot disclose the potential discrepancies if we set distinct thresholds. From this point of view, other creative methods, such as cognitive distance analysis by Samuelsson et al. (2018), the availability of residents to parks in their neighborhood by Poelman (2018), and the public participatory GIS (PPGIS) approach investigated by Samuelsson et al. (2018), Rall et al. (2019), and Samuelsson et al. (2019), may bring enriched insights to limit the uncertainties by cause of our methodology. Furthermore, inevitable uncertainties are associated with our MSPA, as discussed by Vogt et al. (2009) and Wickham et al. (2010), in the preprocessing of our derived land use and land cover dataset as well as in the use of the recently updated toolbox to acquire the GI morphological spatial patterns. To limit such uncertainties, we validated our methodology by first applying it to each local district individually, and then to each type of local districts. Although the use of empirical parameters, such as GI connectivity, edge width, and transition options, among others, with unknown degrees of uncertainty or possible variability introduces some inaccuracy to the outcome of our MSPA, our methodology is based on a well understood approach and has been applied to all sample local districts in the same manner. We aim to strike a balance in a substantial reliability and explore the morphological spatial patterns in typical residential areas. Indeed, this is the first time that the MSPA approach was used to analyze the GI structural connectivity in typical residential areas, and our application provides good examples for further interpretations of the spatial patterns of GI. Both parts (Sections 2.2 and 2.3) of our methodology that build on one another are transferable and traceable with respect to practicability in GI planning and assessment.

5. Conclusions

Three innovative aspects have been presented in this study: first, the application of the MSPA to the typical residential districts to analyze the spatial patterns of urban GI in a growing city; second, exploring the spatial equity of the GI distributions within the typical residential districts; and third, understanding the spatial equity of the urban GI from the morphological perspective.

A growing city like Leipzig encounters the options of either to enlarge the existing GI core areas or enhance the GI bridges, and meanwhile to reinforce the spatial equity of GI for sustainable urban development. Our study provides evidence that enlarging the existing GI core areas would only lead to a limited increase of the spatial equity of GI distribution and, therefore, appears to be less favorable. The option for GI bridges provides structural connectivity from one GI core to different GI cores. Hence, it will substantially contribute to the GI equity. This suggestion is attributed to our combined methodology of MSPA and GI equity measurement (GI-adapted Gini coefficient index). Following from this, urban GI planning should specifically strive to enhance connectivity. GI planning in essence is a strategic planned network to improve the structural and functional connectivity; therefore, it is significant that methods on MSPA and the analysis of the GI-adapted Gini coefficient can reveal the GI spatial patterns and distributions, enabling more informed clues to attain sustainability.

Acknowledgements

This article is part of the integrated project "*Urban Transformations*: *Sustainable urban development towards resource efficiency, quality of life and resilience*" (2014–2020; http://www.ufz.de/stadt). It is being conducted by the Helmholtz Centre for Environmental Research – UFZ within the German Helmholtz Association. We want to thank the Ordnance Survey of the State of Saxony, Germany, for the kind appropriation of the digital orthophotos, elevation and surface models to carry out the prerequisite land-use/land cover classification (© Staatsbetrieb Geobasisinformation und Vermessung Sachsen).The first author would like to express the gratitude to the support from China Scholarship Council.

References

Ahern, J., 2007. Green infrastructure for cities: the spatial dimension. In: Cities of the Future: towards Integrated Sustainable Water and Landscape Management. IWA Publishing. Citeseer.
Ahern, J., 2011. From fail-safe to safe-to-fail: sustainability and resilience in the new urban world. Landsc. Urban Plan. 100, 341–343.
Alberti, M., 2005. The effects of urban patterns on ecosystem function. Int. Reg. Sci. Rev. 28, 168–192.
Alberti, M., Marzluff, J.M., 2004. Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. Urban Ecosyst. 7, 241–265.
Banzhaf, E., Kollai, H., Kindler, A., 2018. Mapping urban grey and green structures for liveable cities using a 3D enhanced OBIA approach and vital statistics. Geocarto Int. 1–18.
Barbati, A., Corona, P., Salvati, L., Gasparella, L., 2013. Natural forest expansion into suburban countryside: gained ground for a green infrastructure? Urban for Urban Gree 12, 36–43.
Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Smart Conservation for the 21st Century. Island, Washington, DC.
Bierwagen, B.G., 2005. Predicting ecological connectivity in urbanizing landscapes. Environ. Plan. Plan. Des. 32, 763–776.
Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), editor, 2007. Leipzig Charta für nachhaltige europäische Städte. BMUB, Berlin.
Cabral, I., Keim, J., Engelmann, R., Kraemer, R., Siebert, J., Bonn, A., 2017. Ecosystem services of allotment and community gardens: a Leipzig, Germany case study. Urban for Urban Gree 23, 44–53.
Cavan, G., Lindley, S., Jalayer, F., Yeshitela, K., Pauleit, S., Renner, F., Gill, S., Capuano, P., Nebebe, A., Woldegerima, T., Kibassa, D., Shemdoe, R., 2014. Urban morphological determinants of temperature regulating ecosystem services in two African cities. Ecol. Indicat. 42, 43–57.
Chardon, J.P., Adriaensen, F., Matthysen, E., 2003. Incorporating landscape elements into a connectivity measure: a case study for the Speckled wood butterfly (Pararge aegeria L.). Landsc. Ecol. 18, 561–573.
Clerici, N., Vogt, P., 2013. Ranking European regions as providers of structural riparian corridors for conservation and management purposes. Int. J. Appl. Earth Obs. Geoinf. 21, 477–483.
Colding, J., 2007. Ecological land-use complementation' for building resilience in urban ecosystems. Landsc. Urban Plan. 81, 46–55.
Colding, J., Barthel, S., 2017. An urban ecology critique on the "Smart City" model. J. Clean. Prod. 164, 95–101.
Coulon, A., Cosson, J., Angibault, J., Cargnelutti, B., Galan, M., Morellet, N., Petit, E., Aulagnier, S., Hewison, A., 2004. Landscape connectivity influences gene flow in a roe deer population inhabiting a fragmented landscape: an individual–based approach. Mol. Ecol. 13, 2841–2850.
Coutts, C., Hahn, M., 2015. Green infrastructure, ecosystem services, and human health. Int. J. Environ. Res. Public Health 12, 9768–9798.
Davies, C., Hansen, R., Rall, E., Pauleit, S., Lafortezza, R., DeBellis, Y., Santos, A., Tosics, I., 2015. Green Infrastructure Planning and Implementation (GREEN SURGE). The Status of European Green Space Planning and Implementation Based on an Analysis of Selected European City-Regions, pp. 1–134.
European Commission (EC), 2012. The Multifunctionality of Green Infrastructure.

Science for Environment Policy. In Depth Reports, March 2012.

European Commission (EC), 2013. Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. In: Green Infrastructure (GI)—Enhancing Europe's Natural Capital. COM(2013) 249 Final.

European Commission (EC), 2016. Nomenclature of territorial units for statistics. Available online: https://ec.europa.eu/eurostat/web/regions-and-cities/overview. (Accessed 4 April 2019).

Fan, P., Xu, L., Yue, W., Chen, J., 2017. Accessibility of public urban green space in an urban periphery: the case of Shanghai. Landsc. Urban Plan. 165, 177–192.

Firehock, K., 2010. A short history of the term green infrastructure and selected literature. Retrieved from. http://www.gicinc.org/PDFs/GI%20History.pdf.

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., Theuray, N., Lindley, S.J., 2008. Characterising the urban environment of UK cities and towns: a template for landscape planning. Landsc. Urban Plan. 87, 210–222.

Goetz, S.J., Jantz, P., Jantz, C.A., 2009. Connectivity of core habitat in the Northeastern United States: parks and protected areas in a landscape context. Remote Sens. Environ. 113, 1421–1429.

Handley, J., Pauleit, S., Slinn, P., Barber, A., Baker, M., Jones, C., Lindley, S., 2003. Accessible natural green space standards in towns and cities: a review and toolkit for their implementation. Engl. Nat. Res. Rep. 526.

Heckert, M., Rosan, C.D., 2016. Developing a green infrastructure equity index to promote equity planning. Urban for Urban Gree 19, 263–270.

Hokit, D.G., Ascunce, M., Ernst, J., Branch, L.C., Clark, A.M., 2010. Ecological metrics predict connectivity better than geographic distance. Conserv. Genet. 11, 149–159.

Holt, A.R., Mears, M., Maltby, L., Warren, P., 2015. Understanding spatial patterns in the production of multiple urban ecosystem services. Ecosyst Serv 16, 33–46.

Kabisch, N., Haase, D., 2014. Green justice or just green? Provision of urban green spaces in Berlin, Germany. Landsc. Urban Plan. 122, 129–139.

Kabisch, N., Strohbach, M., Haase, D., Kronenberg, J., 2016. Urban green space availability in European cities. Ecol. Indicat. 70, 586–596.

Kabisch, S., Ueberham, M., Schlink, U., Hertel, D., Mohamdeen, A., 2018. Local Residential Quality from an Interdisciplinary Perspective: Combining Individual Perception and Micrometeorological Factors, Urban Transformations. Springer, pp. 235–255.

Kazmierczak, A., Armitage, R., James, P., 2010. Urban Green Spaces: Natural and Accessible? the Case of Greater Manchester, UK. Urban Biodiversity and Design. Blackwell Publishing Ltd, Oxford, UK, pp. 383–405.

Khalil, R., 2014. Quantitative evaluation of distribution and accessibility of urban green spaces (Case study: city of Jeddah). Int. J. Geomatics Geosci. 4, 526–535.

Kim, K.H., Pauleit, S., 2007. Landscape character, biodiversity and land use planning: the case of Kwangju City Region, South Korea. Land Use Policy 24, 264–274.

Kupfer, J.A., 2012. Landscape ecology and biogeography: rethinking landscape metrics in a post-FRAGSTATS landscape. Prog. Phys. Geogr. 36, 400–420.

Kuttner, M., Hainz-Renetzeder, C., Hermann, A., Wrbka, T., 2013. Borders without barriers - structural functionality and green infrastructure in the Austrian-Hungarian transboundary region of Lake Neusiedl. Ecol. Indicat. 31, 59–72.

Lauf, S., Haase, D., Kleinschmit, B., 2014. Linkages between ecosystem services provisioning, urban growth and shrinkage - a modeling approach assessing ecosystem service trade-offs. Ecol. Indicat. 42, 73–94.

Li, F., Liu, X.S., Hu, D., Wang, R.S., Yang, W.R., Li, D., Zhao, D., 2009. Measurement indicators and an evaluation approach for assessing urban sustainable development: a case study for China's Jining City. Landsc. Urban Plan. 90, 134–142.

Li, F., Zhang, F., Li, X., Wang, P., Liang, J., Mei, Y., Cheng, W., Qian, Y., 2017. Spatiotemporal patterns of the use of urban green spaces and external factors contributing to their use in central Beijing. Int J Env Res Pub He 14, 237.

Luck, M., Wu, J., 2002. A gradient analysis of urban landscape pattern: a case study from the Phoenix metropolitan region, Arizona, USA. Landsc. Ecol. 17, 327–339.

Maes, J., Zulian, G., Günther, S., Thijssen, M., Raynal, J., 2019. Enhancing resilience of urban ecosystems through green infrastructure (EnRoute). Final Report. In: EUR 29630 EN. Publications Office of the European Union, Luxembourg 2019. https://doi.org/10.2760/602928. JRC115375.

Marcus, L., Colding, J., 2014. Toward an integrated theory of spatial morphology and resilient urban systems. Ecol. Soc. 19.

Matheron, G., 1967. Eléments pour une théorie des milieux poreux. Masson.

McGarigal, K., Marks, B.J., 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. In: Gen. Tech. Rep. PNW-GTR-351. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 122 p.p. 351.

McGarigal, K., Cushman, S.A., Neel, M.C., Ene, E., 2002. FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps.

McRae, B.H., Shah, V.B., 2009. Circuitscape User's Guide. The University of California, Santa Barbara.

Naumann, S., Davis, M., Kaphengst, T., Pieterse, M., Rayment, M., 2011. Design, Implementation and Cost Elements of Green Infrastructure Projects. Final Report, European Commission, Brussels, vol. 138.

Nielsen, A.B., Hedblom, M., Olafsson, A.S., Wiström, B., 2016. Spatial configurations of urban forest in different landscape and socio-political contexts: identifying patterns for green infrastructure planning. Urban Ecosyst. 1–14.

Nuissl, H., Rink, D., Steuer, P., 2005. The consequences of urban sprawl in a context of decline: the case of Leipzig. UFZ-Diskussionspapiere, 7/2005, Leipzig.

Ostapowicz, K., Vogt, P., Riitters, K.H., Kozak, J., Estreguil, C., 2008. Impact of scale on morphological spatial pattern of forest. Landsc. Ecol. 23, 1107–1117.

Pauleit, S., Duhme, F., 2000. Assessing the environmental performance of land cover types for urban planning. Landsc. Urban Plan. 52, 1–20.

Pauleit, S., Liu, L., Ahern, J., Kazmierczak, A., 2011. Multifunctional Green Infrastructure Planning to Promote Ecological Services in the City.

Pauleit, S., Ambrose-Oji, B., Andersson, E., Anton, B., Buijs, A., Haase, D., Elands, B., Hansen, R., Kowarik, I., Kronenberg, J., 2018. Advancing Urban Green Infrastructure in Europe: Outcomes and Reflections from the GREEN SURGE Project. Urban for Urban Gree.

Pauleit, S., Zölch, T., Hansen, R., Randrup, T.B., van den Bosch, C.K., 2017. Nature-based solutions and climate change—four shades of green, Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Springer, Cham, pp. 29–49.

Pincetl, S., Gearin, E., 2013. The reinvention of public green space. Urban Geogr. 26, 365–384.

Poelman, H., 2018. A walk to the park? Assessing access to green areas in Europe's cities., Directorate-General for Regional and Urban Policy. Available online: https://ec.europa.eu/regional_policy/sources/docgener/work/2016_03_green_urban_area.pdf (Accessed 17 October 2018).

Rall, E., Hansen, R., Pauleit, S., 2019. The added value of public participation GIS (PPGIS) for urban green infrastructure planning. Urban for Urban Gree 40, 264–274.

Ramos-Gonzalez, O.M., 2014. The green areas of San Juan, Puerto Rico. Ecol. Soc. 19.

Riitters, K.H., 2011. Spatial Patterns of Land Cover in the United States: a Technical Document Supporting the Forest Service 2010 RPA Assessment. Gen. Tech. Rep. SRS-136, vol. 64. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, pp. 1–64, 136.

Romero, H., Vasquez, A., Fuentes, C., Salgado, M., Schmidt, A., Banzhaf, E., 2012. Assessing urban environmental segregation (UES). The case of Santiago de Chile. Ecol. Indicat. 23, 76–87.

Samuelsson, K., Giusti, M., Peterson, G.D., Legeby, A., Brandt, S.A., Barthel, S., 2018. Impact of environment on people's everyday experiences in Stockholm. Landsc. Urban Plan. 171, 7–17.

Samuelsson, K., Colding, J., Barthel, S., 2019. Urban resilience at eye level: spatial analysis of empirically defined experiential landscapes. Landsc. Urban Plan. 187, 70–80.

Saura, S., Torne, J., 2009. Conefor Sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity. Environ. Model. Softw 24, 135–139.

Saura, S., Vogt, P., Velázquez, J., Hernando, A., Tejera, R., 2011. Key structural forest connectors can be identified by combining landscape spatial pattern and network analyses. For. Ecol. Manag. 262, 150–160.

Soille, P., 2003. On the morphological processing of objects with varying local contrast. In: International Conference on Discrete Geometry for Computer Imagery. Springer, pp. 52–61.

Soille, P., 2013. Morphological Image Analysis: Principles and Applications. Springer Science & Business Media.

Soille, P., Vogt, P., 2009. Morphological segmentation of binary patterns. Pattern Recognit. Lett. 30, 456–459.

Stadt Leipzig (online). Wasser und Stadtgrün: “Masterplan Grün Leipzig 2030”. https://www.leipzig.de/freizeit-kultur-und-tourismus/parks-waelder-und-friedhoefe/masterplan-gruen/accessed 2019/03/01.

Stadt Leipzig, 2003. Umweltqualitätsziele und –standards für die Stadt Leipzig. Stadt Leipzig, Der Oberbürgermeister, Amt für Umweltschutz. Juli 2003.

Stadt Leipzig, 2012. Statistics: bevölkerungsbestand beim leipzig-informationssystem. Available online: https://statistik.leipzig.de/statdist/table.aspx?cat=2&rub=1. (Accessed 10 February 2019).

Stadt Leipzig, 2018. Integriertes Stadtentwicklungskonzept Leipzig 2030. Accessed 2019/03/01. https://www.leipzig.de/bauen-und-wohnen/stadtentwicklung/stadtentwicklungskonzept-insek/.

Sutcliffe, O.L., Bakkestuen, V., Fry, G., Stabbetorp, O.E., 2003. Modelling the benefits of farmland restoration: methodology and application to butterfly movement. Landsc. Urban Plan. 63, 15–31.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G., Gaston, K.J., 2007. Urban form, biodiversity potential and ecosystem services. Landsc. Urban Plan. 83, 308–317.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kazmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: a literature review. Landsc. Urban Plan. 81, 167–178.

Van der Zanden, E.H., Verburg, P.H., Mucher, C.A., 2013. Modelling the spatial distribution of linear landscape elements in Europe. Ecol. Indicat. 27, 125–136.

Vogt, P., Riitters, K., 2017. GuidosToolbox: universal digital image object analysis. Eur J Remote Sens 50, 352–361.

Vogt, P., Riitters, K.H., Estreguil, C., Kozak, J., Wade, T.G., Wickham, J.D., 2006. Mapping Spatial Patterns with Morphological Image Processing. Landscape Ecol 22, 171–177.

Vogt, P., Riitters, K.H., Iwanowski, M., Estreguil, C., Kozak, J., Soille, P., 2007. Mapping landscape corridors. Ecol. Indicat. 7, 481–488.

Vogt, P., Ferrari, J.R., Lookingbill, T.R., Gardner, R.H., Riitters, K.H., Ostapowicz, K., 2009. Mapping functional connectivity. Ecol. Indicat. 9, 64–71.

Wang, J., Banzhaf, E., 2018. Towards a better understanding of Green Infrastructure: a critical review. Ecol. Indicat. 85, 758–772.

Whitford, V., Ennos, A.R., Handley, J.F., 2001. City form and natural process" - indicators for the ecological performance of urban areas and their application to Merseyside, UK. Landsc. Urban Plan. 57, 91–103.

Wickham, J.D., Riitters, K.H., Wade, T.G., Vogt, P., 2010. A national assessment of green infrastructure and change for the conterminous United States using morphological image processing. Landsc. Urban Plan. 94, 186–195.

Wickham, J., Riitters, K., Vogt, P., Costanza, J., Neale, A., 2017. An inventory of

continental U.S. terrestrial candidate ecological restoration areas based on landscape context. Restor. Ecol. 25, 894–902.
Wickop, E., Böhm, P., Eitner, K., Breuste, J., 1998. Qualitätszielkonzept für Stadtstrukturtypen am Beispiel der Stadt Leipzig. UFZ-Bericht 14, 156.
Wüstemann, H., Kalisch, D., Kolbe, J., 2017. Access to urban green space and environmental inequalities in Germany. Landsc. Urban Plan. 164, 124–131.
Xu, C., Haase, D., Pribadi, D.O., Pauleit, S., 2018. Spatial variation of green space equity and its relation with urban dynamics: a case study in the region of Munich. Ecol. Indicat. 93, 512–523.