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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

* Corresponding author who will handle correspondence at all stages of refereeing and publication, also post-publication

UFZ - Helmholtz Centre for Environmental Research, Department Urban and
Environmental Sociology, Permoserstraße 15, 04318 Leipzig, Germany
Tel: +49(0)341 2351557

Technical University of Munich, TUM School of Life Sciences, Chair for Strategic Landscape Planning and Management, Emil-Ramann-Str. 6, 85354 Freising, Germany.

Email: jingxia.wang@ufz.de; jingxia.wang@tum.de

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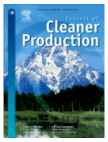
Abstract

Urbanization processes spur the need for urban green infrastructure (GI) to support the well-being of urban dwellers and to 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. Combining MSPA with a spatial equity measurement to analyze three typical residential areas, i.e. (semi-)detached houses, linear multistorey housing estates, and perimeter blocks respectively. 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 which 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.



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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 it has been defined as the strategically planned and managed networks of natural and semi-natural lands, features and green spaces, and terrestrial, freshwater, 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 (also known as "gray infrastructure") has been described as the functional support system of urbanized areas (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 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 ESS (Samuelsson et al., 2019) provided by urban GI. Amongst the multiple objectives GI has (EC, 2013) are the promotion of biodiversity, climate change adaptation, providing 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 ecosystem services (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 lights on the connectivity (Samuelsson et al., 2019) and configuration of urban GI. Allocation of GI is influenced by the character of gray infrastructure, i.e. 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), determines 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., 2009; Vogt et al., 2007; 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 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 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 instances, the Conefor Sensinode tool (Saura and Torne, 2009) quantifying habitat patches for connectivity, by calculating nodes, links, graph-based metrics including 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. They are widely utilized to analyze structural landscape metrics and connectivity, but they are all rooted in graph, network, and circuit theory (Kupfer, 2012), 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 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), neither landscape metrics (structural indices) nor graph-based approaches. Indeed, MSPA is a mathematical morphological algorithm that performs a segmentation analysis of foreground objects against 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, MSPA offers an effective approach to investigate GI in heterogeneous urban areas, allowing to identify and quantify 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), to 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 in urban areas (Ramos-Gonzalez, 2014), and in this paper it 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 distribution and 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). To explore urban GI spatial patterns for equity in typical residential areas, and our specific objectives were: 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 km² (Fig. 1). With 596,517 inhabitants in 2018, it is the largest city in Saxony with a population density of 2008 inhabitants per km². 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 a main reason why it is one of Germany's greenest cities with an average of 254 m² 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. 1,240 hectares) (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. Beyond, Leipzig prides itself with its eagerness in sustainable urban development (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), 2007; Stadt Leipzig, 2019). As part of these efforts, urban planning makes major endeavors in re-densifying the municipal space thus preventing urban sprawl. As a consequence, land development processes have been leading to 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, 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. To maintain a green city that secures a high environmental quality of urban life and to offer housing and public infrastructure is a major current challenge 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.

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

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 block alignment with 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 (Fig. 2 & 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. 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). Single and semi-detached (or duplex) family houses started in the 20th century in large designated settlement areas and continue to be constructed up to date, nowadays rather patchy and dispersed throughout the city.

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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

We apply and test our method for selected sample districts (Fig. 3), which were considered as fairly representative for the three residential types. For the reason of even urban coverage we select three sample districts each: typical local districts for the Wilhelminean 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 '80s, we choose two local districts from this vast area in the southwestern part of the city (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 decide 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 9 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 does not include the local districts at the outskirts of the city, because most of them were incorporated into the City of Leipzig between 1993 and 2000 as a municipal area reform and 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.

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

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 are processed in an object-based image analysis (OBIA) approach described by Banzhaf et al. (2018) in which the different datasets are all rescaled to 1 meter 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 morphological patterns of GI at 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 include all urban population with first and second place of residency living in Leipzig. By also considering those with a second residency we pay tribute to international students, commuters and so forth 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 and his colleagues 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 MSPA has continued to be developed for landscape ecological studies. In this paper we use 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 comprise the reclassification of spatial data into a binary map by using ArcGIS 10.6 compared to Soille and Vogt (2009) and Wickham et al. (2017), which include 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 GI morphological patterns, setting all other built-up structures (including railways, paved surfaces, commercial buildings etc.) to 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 there was a ready-made MSPA toolbox available, we decided to customize it 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; iii) resampling 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 meter. Otherwise there are potential risks of losing information due to the change of spatial resolution, because without aforementioned preprocessing, our input data is restricted to a square map of 10000 * 10000 pixels for 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 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.

Table 1 Classification of morphological spatial patterns

MSPA classes	Definitions
Core	GI surrounded by all sides (8-connectivity) by GI and greater than 3 meter 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 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 are shaped by perforations (inner edges).
Edge	Transition zone between GI and built-up areas
Islet	Unconnected class without core.

2.4. Data processing for 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, more recently a growing number of references (Kabisch and Haase, 2014; Li et al., 2017; Wüstemann et al., 2017; Xu et al., 2018) 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 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 meters (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 to measure the spatial equity of GI distribution in local districts with different dominant residential types. It is expressed as:

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

Where P is the total population of the local district, P_i is the population number of grid cell i, B is the cumulative share of GI in a 300 m buffer around grid cell i. The GI adapted Gini coefficient ranges from 0 and 1, with 0 represents total equity while 1 indicates absolute inequity.

The GI adapted Gini coefficient was calculated according to the following steps. Firstly, GI patches were selected with a minimum size of 2 ha and the population density for 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. Secondly, each sample local district was intersected with a 100m × 100m grid file in ArcGIS 10.6, and grids with their centroids located in each sample district were collected. Thirdly, for each sample local district, the population number within each grid cell and the area of GI (selected in the first step) within a 300m buffer around the centroid of the grid cell was 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.

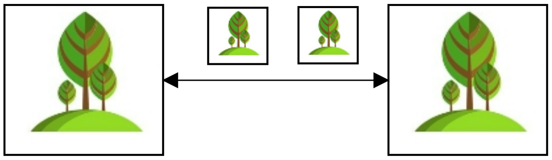
3. Results

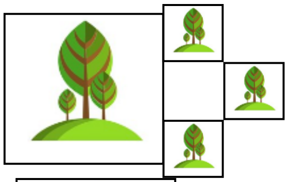
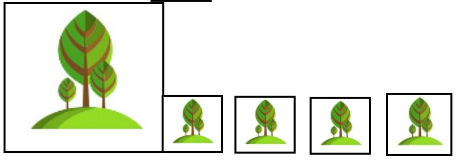
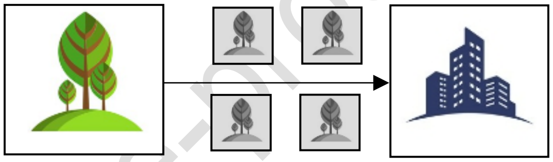
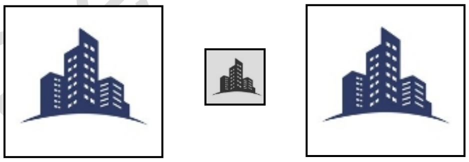
3.1. Morphological spatial patterns analysis for typical residential areas

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 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 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 *GI 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.

Table 2 Conversion of 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	

GI core in Table 2 is usually composed of a broad spectrum of types of green and GI elements, encompassing currently primary functioning GI. Other GI spatial patterns such as bridge, loop, branch etc., however, are 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) which 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 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.

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

3.1.2. Comparing 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 overall spatial patterns were quite similar from GI core to islet.

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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)

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 which connect to 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, 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 there was an extremely high pressure on urban dwellings due to 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: Wilhelminian style perimeter blocks in 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 following section 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, as the smaller Gini coefficient indicates a higher equity of potential access to the same amount of GI and vice versa.

In addition, 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 of 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 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 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 those historical building complexes. Consequently, residents in such typical residential districts, e.g. Neustadt-Neuschönefeld, Gohlis-Mitte, or Südvorstadt, are probably having 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 easier access nearby GI for further recreation.

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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

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 one 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 GI distributions show usually more equity in these predominant local districts.

For the same type of building structures, the spatial patterns of GI are rather similar as Figures 5 & 7 show. For instance, for those local districts dominated by (semi-)detached houses the proportions of both bridge and edge are quite similar. Therefore, GI cores are relatively well connected, while the findings also imply potential vulnerability of GI since edge is usually a transition zone between GI and built-up areas. The differences are small in the proportion of edge and bridge areas in (semi-)detached dominated local districts while they are larger in those local districts dominated by linear multistorey housing and perimeter blocks. In particular for the latter, 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.

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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)

4. Discussion

We analyzed the spatial patterns in those local districts, which represent 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 combine 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 GI spatial patterns of our sampled local districts and their structural connectivity. It enables us to discuss how these urban GI patterns affect ecosystem functions respectively. GI cores which contain 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 where there are 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) since 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).

To compare urban GI morphological spatial patterns in different types of residential areas, we discover that 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 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 impacts on structural connectivity of GI but their implications for the corresponding spatial equity of GI distributions are still unclear. At present, we are not yet able to advice whether more loops are needed to provide spatial distributions of GI more evenly.

To analyze spatial equity of GI, we used Gini coefficient. 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 access nearby GI for further recreation much easier. 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). GI distributions are relatively unequal in districts prevailed by linear multistorey housing and perimeter blocks. In those 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 firstly pictures the variations in the spatial equity of GI distributions for different types of residential areas, and secondly it reveals substantial impacts on potential recreation functions of GI.

Combined MSPA with spatial equity of GI serves to our novel exploration for the multiple relationships between spatial patterns and equity of GI distributions. In general, bridges which connect from one GI core to a different GI core have a significant influence not only on 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 GI core areas. GI bridges enhance the connectivity between GI cores and significantly increase equity on green spaces in linear multi-storey 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). 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 so that many residents are close to them (Samuelsson et al., 2018), 2) the ecological connectivity of urban GI, so that both the urban dwellers and the flora and fauna themselves could cognitively connected with the Biosphere (Colding, 2007; Colding and Barthel, 2017).

Overall, 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 to calculate Gini coefficient, we defined a 300 m buffer around residential areas. The 300m threshold was quite influential to measure citizens' proximity to urban green spaces in lots of cities such as Greater Machester, UK (Kazmierczak et al., 2010), the City of Jeddah, Egypt (Khalil, 2014), and Shanghai, China (Fan et al., 2017). However, we are not able to 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 enrich insights to limit the uncertainties by cause of our methodology. Furthermore, there are inevitable uncertainties 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 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 etc. 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 applied to all sample local districts in the same way. We aim to strike a balance between 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 GI structural connectivity in the typical residential areas, and our application provides good examples for further interpretations of spatial patterns of GI. Both parts (see Section 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: firstly, the application of MSPA to typical residential districts to analyze spatial patterns of urban GI in a growing city; secondly, exploring spatial equity of GI distributions within typical residential districts; thirdly, understanding the spatial equity of urban GI from the morphological perspective.

A growing city like Leipzig encounters the options of either to enlarge existing GI core areas or to enhance GI bridges, and meanwhile to reinforce 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 spatial equity of GI distribution and therefore seems less favorable. The option for GI bridges provides structural connectivity from one GI core to different GI cores. It will therefore substantially contribute to 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. It is, therefore, significant that methods on MSPA and the analysis of the GI adapted Gini coefficient can reveal the GI spatial patterns and distributions thus enabling more informed clues to attain sustainability.

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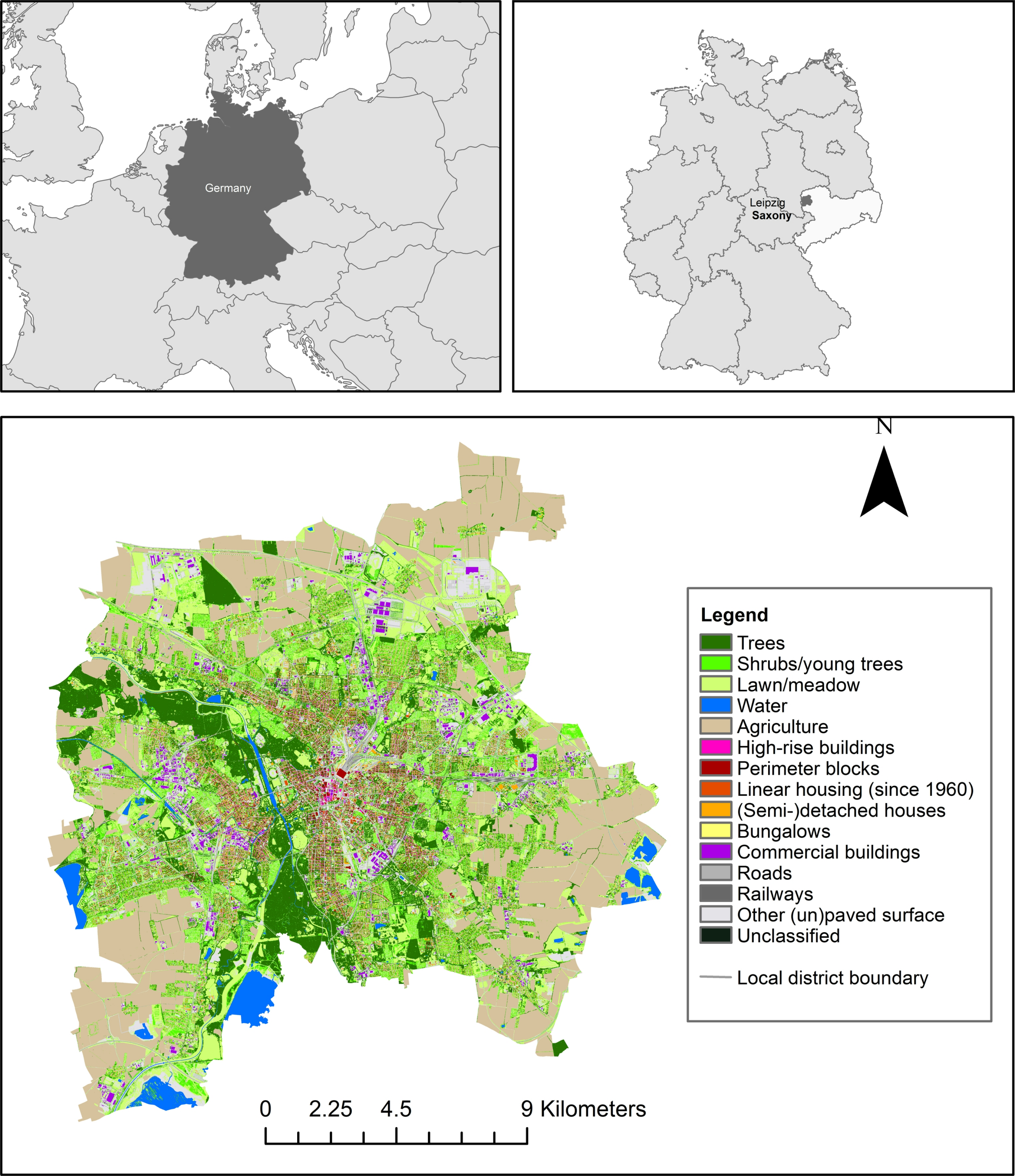
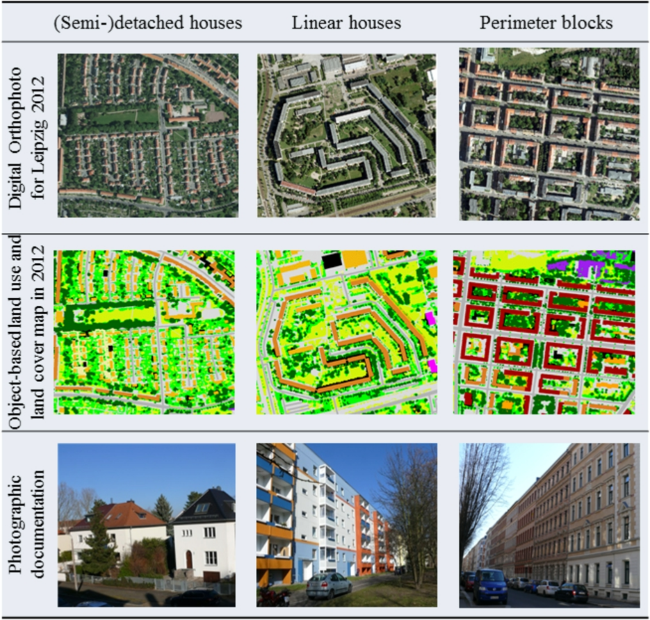
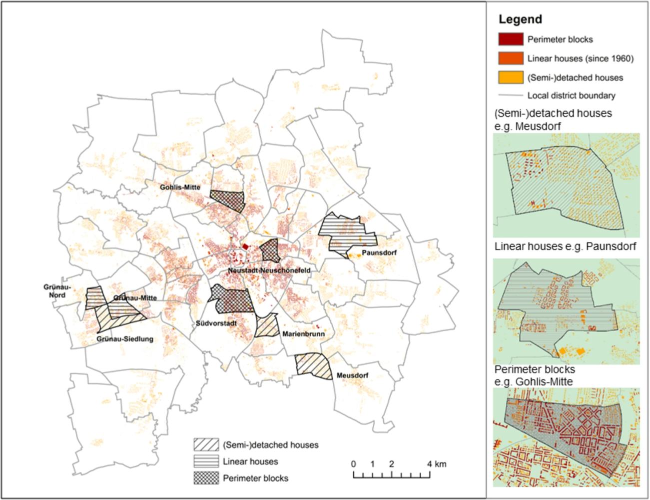
Highlights (include 3 to 5 bullet points maximum 85 characters, including spaces, per bullet point)

- Morphological spatial pattern analysis serves to strategic urban GI planning
- GI bridges contribute to ecological structural connectivity and spatial equity of GI
- An observed tendency of more equal access to green spaces in typical residential areas.
- GI cores do not firmly ascertain a high level of spatial equity
- GI bridges are advised to restore or build for more equal green spaces


Germany
Leipzig
Saxony
N
Legend
Trees
Shrubs/young trees
Lawn/meadow
Water
Agriculture
High-rise buildings
Perimeter blocks
Linear housing (since 1960)
(Semi-)detached houses
Bungalows
Commercial buildings
Roads
Railways
Other (un)paved surface
Unclassified
Local district boundary
0
2.25
4.5
9 Kilometers


(Semi-)detached houses
Linear houses
Perimeter blocks
Digital Orthophoto for Leipzig 2012
Object-based land use and land cover map in 2012
Photographic documentation


Legend
Perimeter blocks
Linear houses (since 1960)
(Semi-)detached houses
Local district boundary
(Semi-)detached houses e.g. Meusdorf
Linear houses e.g. Paunsdorf
Perimeter blocks e.g. Gohlis-Mitte
Gohlis-Mitte
Paunsdorf
Neustadt-Neuschönefeld
Grünau-Nord
Grünau-Mitte
Grünau-Siedlung
Südvorstadt
Marienbrunn
Meusdorf
(Semi-)detached houses
Linear houses
Perimeter blocks
0 1 2 4 km

Extraction from (semi-)detached houses Marienbrunn

Extraction from linear houses Paunsdorf

Extraction from perimeter blocks Gohlis-Mitte

GI spatial patterns map

🟩 Core

🟥 Bridge

🟨 Loop

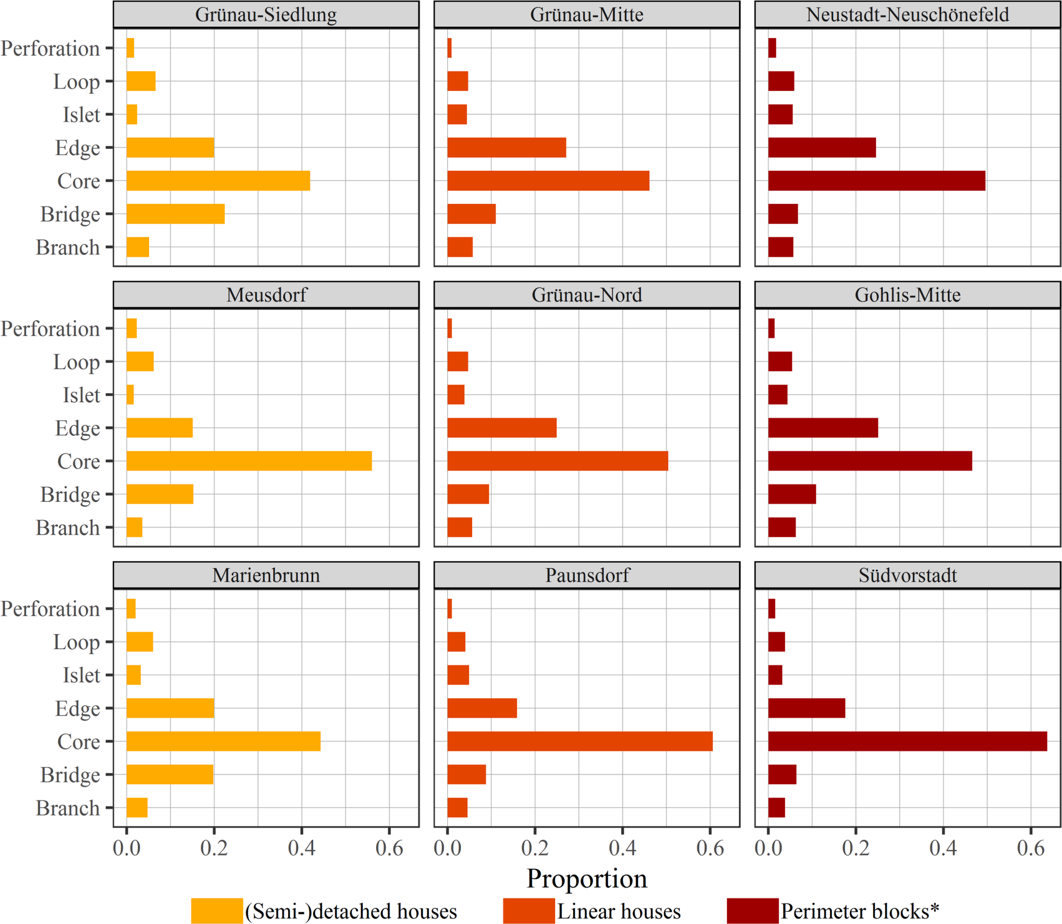
🟧 Branch

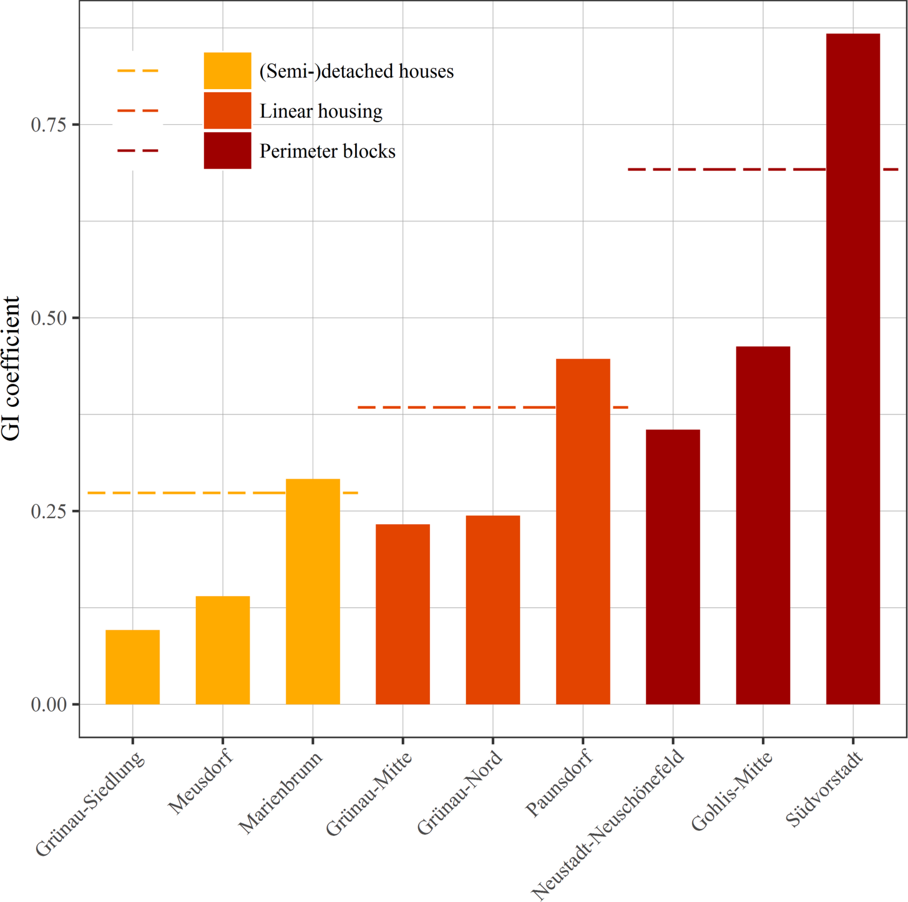
🟦 Perforation

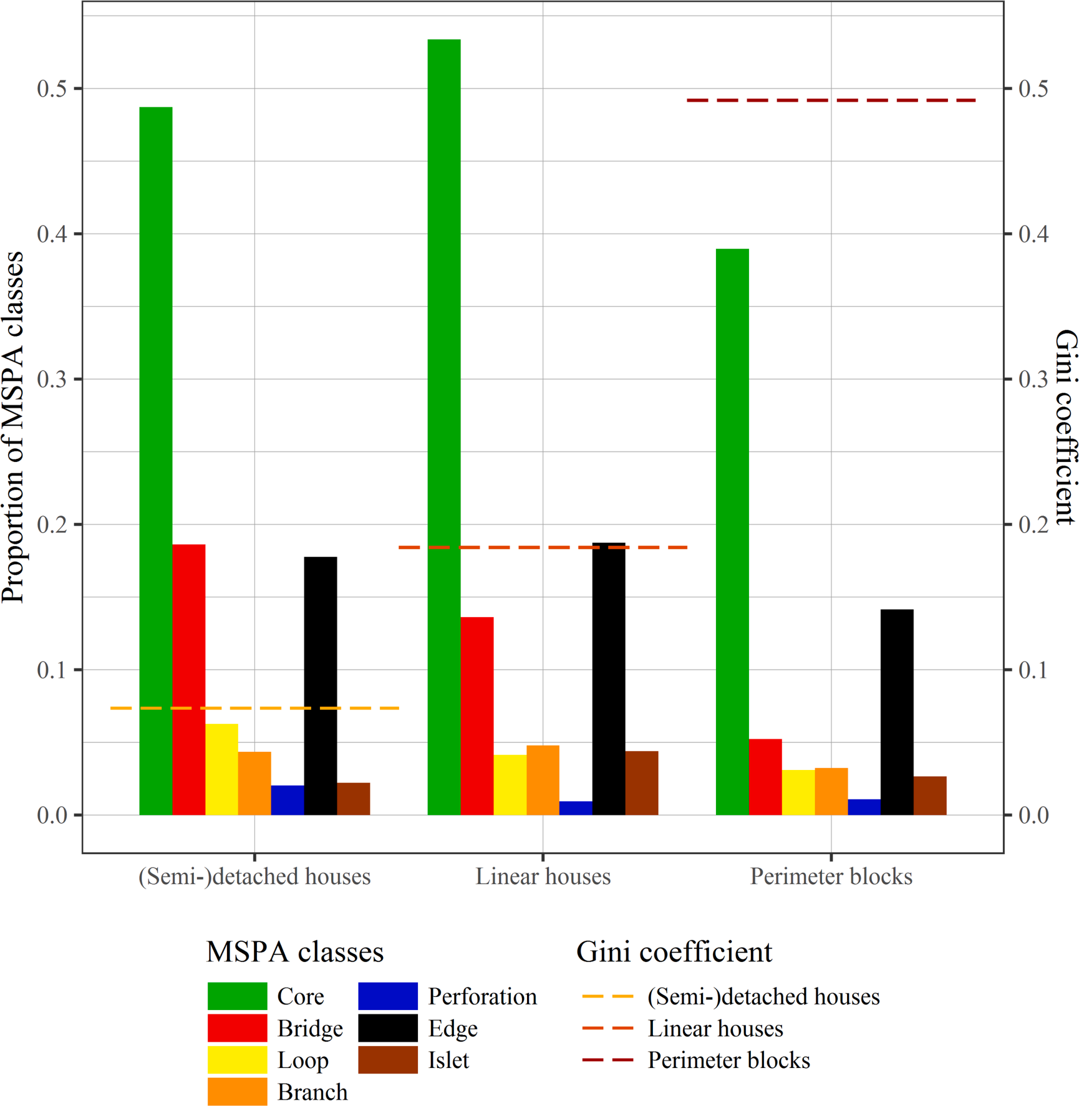
⬛ Edge

🟫 Islet

⬜ Background


Grünau-Siedlung
Grünau-Mitte
Neustadt-Neuschönefeld
Meusdorf
Grünau-Nord
Gohlis-Mitte
Marienbrunn
Paunsdorf
Südvorstadt
Perforation
Loop
Islet
Edge
Core
Bridge
Branch
0.0
0.2
0.4
0.6
Proportion
(Semi-)detached houses
Linear houses
Perimeter blocks*


(Semi-)detached houses
Linear housing
Perimeter blocks
GI coefficient
0.75
0.50
0.25
0.00
Grünau-Siedlung
Meusdorf
Marienbrunn
Grünau-Mitte
Grünau-Nord
Paunsdorf
Neustadt-Neuschönefeld
Gohlis-Mitte
Südvorstadt


Proportion of MSPA classes
Gini coefficient
0.0
0.1
0.2
0.3
0.4
0.5
(Semi-)detached houses
Linear houses
Perimeter blocks
MSPA classes
Core
Bridge
Loop
Branch
Perforation
Edge
Islet
Gini coefficient
(Semi-)detached houses
Linear houses
Perimeter blocks