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Greenery in urban morphology: a comparative analysis of differences in urban green space accessibility for various urban structures across European cities

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ABSTRACT. The understanding of urban social-ecological systems requires integrated and interdisciplinary methods. This paper explores differences in the accessibility of urban green spaces (UGS) based on urban morphology. In contrast to other comparative analyses that followed simplified quantification of UGS provision and/or omitted the impact of morphological properties of urban space, this study proposes three improvements. First, it uses the share of UGS in the service area of 300 m walking distance around each residential building in a city as a measure of UGS provision. Second, it includes the potential physical accessibility of UGS as warranted by key actors, such as owners or managers, who decide whether UGS are open or not to potential users. Third, it links UGS accessibility and heterogeneous urban structures. We developed a mixed-methods analysis that combines multiple data sources regarding UGS, the spatial distribution of residential buildings, and street networks. We conducted our analysis in five case-study cities (Barcelona, Halle, Lodz, Oslo, and Stockholm). Our findings suggest that the urban structures where the human–environment interaction transformed the space (such as in the core city areas) are characterized by limited UGS in the service area. Urban structures that are less transformed by human activity (especially suburbia) have the highest share of selected UGS in the service area. In addition, even if the share of UGS in the service area is high, many of them might have limited physical accessibility. In the broader sense, this highlights that social-ecological processes are linked to urban form and cannot be separated in an analysis. Therefore, social-ecological systems could be better understood through the lens of urban morphology.

Key Words: *GIS; land use; landscape metrics; social-ecological systems; spatial analysis; urban green space management*

INTRODUCTION

The understanding of urban social-ecological systems requires the integration of data and methods from various fields. One of the promising—but still insufficiently explored—areas of such integration is to link the disparities in the provision of urban green spaces (UGS) (Andersson et al. 2019, Pauleit et al. 2019, Herreros-Cantis and McPhearson 2021) and urban morphology (Dennis et al. 2018, Marcus et al. 2019, Riechers et al. 2020). In general terms, urban morphology refers to the study of both urban form, i.e., the physical elements that structure and shape cities like streets, buildings, and plots, and the stakeholders and processes that shape it (Kropf 2018, Oliveira 2019b). As a source of knowledge on the organization of cities, urban morphology informs various aspects of life in cities, such as the flow of benefits from UGS to the inhabitants (Oliveira 2019b, Andersson et al. 2019).

As Zou and Wang (2021) highlighted, in the last decade, UGS have been studied through the lens of urban morphology (Šćitaroci and Marić 2019, Whitehand 2019). Although there have been attempts to integrate the analysis of urban forms and urban inequalities (Oliveira 2021), studies conducted by urban morphologists did not discuss the deeper disparities in UGS provision (Kabisch et al. 2016) and benefits provided by UGS—urban ecosystem services (Kabisch 2019, Barton et al. 2020). At the same time, studies that focused on quantifying UGS disparities typically neglected the urban morphology perspective (Zhang et al. 2020a).

There are several potential advantages of incorporating urban morphology into the analysis of disparities in UGS provision (Zou and Wang 2021). One of the roles of urban morphology is to identify the recurring spatial patterns in the structure, formation, and transformation of the built environment (Fleischmann et al. 2021a). A combined perspective of urban morphology and UGS provision can also foster the debate on the density dilemma and the related duality of making cities more livable and sustainable (Neuman 2005, Wolff and Haase 2019). Urban morphology can be used to delimit homogeneous urban structures that could be used for intra-city comparisons of UGS provision and disparities (Grafius et al. 2018). In addition, linking UGS-related disparities and urban structures could help to better understand the background of these disparities and provide an informed background for UGS provision standards (Badiu et al. 2016, Boulton et al. 2018). Such an integrated analysis could help avoid oversimplification when interpreting UGS-related disparities and their potentially biased quantification.

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This study contributes to the emerging debate on how to better understand social-ecological systems (Marcus et al. 2019, Riechers et al. 2020). In contrast to other comparative analyses that followed simplified quantification of UGS provision and/or omitted the impact of morphological properties of urban space, this study proposes three improvements. First, it uses the share of UGS in the service area of 300 m walking distance around each residential building in a city as a measure of UGS provision. Second, it includes the potential physical accessibility of UGS as warranted by key actors, such as owners or managers, who decide on whether UGS are open or not to potential users. Third, it links UGS accessibility and heterogeneous urban structures. We aim to quantify the disparities in the provision of UGS, characterized by different levels of potential accessibility, for various urban structures, delimited through the lens of urban morphology. We hypothesize that UGS provision and the inequalities regarding its provision differ between urban structures. We applied mixed-methods analysis for multisource spatially explicit data on UGS, residential buildings, and street networks in five case-study cities (Barcelona, Halle, Lodz, Oslo, and Stockholm).

The remainder of this article is divided into five sections. The "Materials and Methods" section justifies the selection of case-study cities, data sources, and methods used to quantify disparities in UGS provision for various urban structures. The "Results" section contains the findings, which are then discussed in the subsequent section in the broader context of using multiple spatial scales, such as the level of residential buildings and urban structures, to evaluate UGS provision. We also discuss the results from the perspective of the three systemic filters that mediate the flow of benefits that UGS provide to city inhabitants (Andersson et al. 2019, 2021) and suggest how urban morphology could improve the understanding of social-ecological systems. We end with some concluding remarks.

MATERIALS AND METHODS

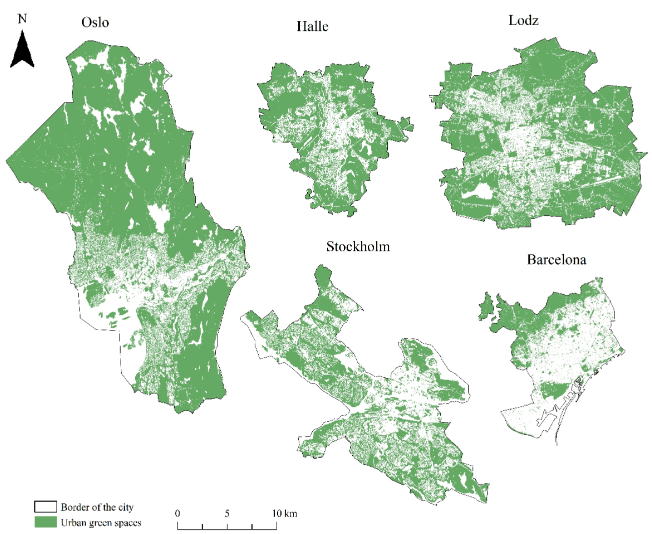
Case-study Cities

Our analysis involves five cities that represent different geographical locations in Europe: Barcelona (Spain), Halle (Germany), Lodz (Poland), Oslo (Norway), and Stockholm (Sweden). They differ in terms of population density and size, and the challenges to UGS planning. This diversity makes them representative of different urban forms. In particular, at the spatial level of residential buildings, the case-study cities vary from 51,342 to 83,605 observations for Halle and Oslo, respectively. In terms of UGS coverage, the cities differ from 33.3% to 73.4% for Barcelona and Oslo, respectively (Table 1). In Oslo, UGS includes the protected peri-urban forest of the Marka area. Protection of the greenbelt has constrained urban growth, leading to densification within the built zone, which makes it a relatively compact city, but not as compact as, for example, Barcelona. This makes our sample of cities diverse enough to represent European differences in UGS coverage and the pan-European context of UGS planning (Kabisch et al. 2016, Artmann et al. 2017, Wolff and Haase 2019). A brief comparison of the case-study cities is presented in Fig. 1 and Table 1.

Databases

This study required data on UGS, the spatial distribution of residential buildings, and the street network. The majority of the data came from open geographical data sources, such as OpenStreet Map or Copernicus, making our analysis replicable in other cities. The list of databases, each with a brief description, is presented in Table 2.

Fig. 1. Case study cities and UGS coverage.



Methods

The identification of spatially explicit disparities in UGS provision through the lens of urban morphology consists of seven phases: (1) classifying UGS according to their potential physical accessibility, (2) quantifying spatially explicit UGS provision, (3) operationalizing the urban structure, (4) delimiting urban blocks, (5) quantifying urban form characters, (6) identifying urban structures, and (7) quantifying spatially explicit inequalities in UGS provision for different urban structures. In the following subsections, each of these phases is described in detail.

Classifying urban green spaces according to their potential physical accessibility

We aimed to obtain the most comprehensive categorization of UGS to consider their potential physical accessibility (Biernacka and Kronenberg 2018, 2019) and to discuss their provision from the broader perspective of the three systemic filters that affect the flow of benefits from UGS to city inhabitants: institutions, infrastructures, and preferences (Andersson et al. 2019, 2021; see also the subsection "The context of the mediating filters framework"). Using ArcGIS 10, we combined data on UGS from multiple sources (Table 2) and classified them into 21 UGS categories (for data processing details, see Append. 1).

We classified UGS based on their potential physical accessibility, which is a particular aspect of UGS provision (Biernacka and Kronenberg 2018, 2019). Based on previous studies (Biernacka and Kronenberg 2018, 2019), we assigned different levels of physical accessibility to each of the 21 UGS categories to account for the influence that key actors, e.g., owners or managers, have on whether they are open or not to potential users. We approximated the different levels of physical accessibility by

Table 1: Main characteristics of case study cities.

Indicator / City	Barcelona	Halle	Lodz	Oslo	Stockholm
Location	Southwestern Europe, Spain	Central Europe, Germany	Central-Eastern Europe, Poland	North Europe, Norway	North Europe, Sweden
Population[1]	1,620,343	239,173	687,702	673,469	962,154
Total area[1] (km^2)	102	135	293	454	188
Population density (population/km^2)	15,886	1,772	2,347	1,483	5,118
Number of residential buildings[2]	61,228	51,342	52,122	83,605	62,218
UGS coverage (% of city area)[2]	33.6	69.8	69.8	73.4	50.4

[1] Eurostat, Instituto Nacional de Estadistica, Statistics Sweden.
[2] According to the database described in Table 2.

categorizing UGS into public (high physical accessibility), semi-public (medium physical accessibility), and private (low physical accessibility) (see Table 3).

Quantifying spatially explicit urban green space provision

We quantified the provision of UGS at the finest spatial resolution possible, i.e., separately for each residential building. For each of the 310,515 residential buildings in the five cities, we calculated the percentage of each of the 21 UGS categories within a service area of 300 m walking distance around each residential building's centroid. We chose the service area approach as it is often considered particularly meaningful because it refers to where people walk, which is how they typically reach their local UGS. In particular, in contrast to a circular buffer, it does not overestimate the area that can be reached by pedestrians, hence, compared with other methods, it represents an improved measure of UGS provision (Lin et al. 2020, Wolff 2021).

The service area of 300 m refers to the concept of "pedestrian shed" promoted by sustainable urbanism and interpreted as a core catchment area, i.e., the area of access to the most important, daily-used facilities (Vale et al. 2018). Additionally, it is in line with Natural England's recommendation that each person should have green space no further than 300 m or a 5 min walk from their home (Mears et al. 2019). For this purpose, we used Network Analysis Toolbox in ArcGIS 10.5.

Operationalizing the urban structure

Urban morphology addresses the various aspects of urban form, ranging from physical components of urban space, through their interactions with inhabitants, to land uses and functions (Fleischmann et al. 2021b). We focused on selected physical aspects of urban form for which we applied methods from landscape ecology (spatial metrics) and statistics (dimensionality-reduction and cluster analysis) (Clifton et al. 2008, Zhang et al. 2019).

To avoid terminological inconsistency and to overcome simplifications in quantitative analysis of urban form (Fleischmann et al. 2021b), in this study, we use the term "urban structure" to define an area within a city that is homogeneous in terms of selected urban form characters and that differs from the surrounding areas. We defined urban form character, following Fleischmann et al. (2021b), as a "characteristic (or feature) of one kind of urban form that distinguishes it from another kind." The basic spatial unit used to delimit urban structures was the urban block—an area bounded on each side by roads. Our understanding of urban structure is similar to what others described as a morphological region, i.e., "an area that has a unit in respect of its form, that distinguishes it from surrounding areas" (Oliveira 2019a), and urban tissue, i.e., "an organic whole that can be seen according to different levels of resolution" (Kropf 1996, Oliveira 2022).

Delimiting urban blocks

It was necessary to delimit each city into our basic spatial units —urban blocks—to identify urban structures. To separate one urban block from another, we mainly used the street network (Grippa et al. 2018). To identify urban blocks for suburbs, we supplement the street network with railways and/or natural borders, such as the coastline.

Delimiting urban blocks in each city followed the following steps: (1) we cleaned the street network of bridleways, cycleways, footways, and paths as they do not often act as a physical barrier that separates areas, (2) we supplemented the street network with rail and tram lines, and natural borders because they usually divide space into disconnected parts, and (3) we added the city borders.

Based on the above set of polylines, we created the initial polygons, which represented urban residential blocks (with at least one residential building located within a block) and urban non-residential blocks (which were mostly polygons with transport infrastructure). Then, we provided a visual inspection of the initial urban blocks and cleaned them of undesirable polygons that result from multilane roads, functional roads near crossroads, or highway ramps. This resulted in the final set of residential and non-residential urban blocks. Only the former was further considered when identifying urban structures.

Quantifying urban form characters

We quantified urban form characters for each urban block using 15 spatial metrics (Zhang et al. 2019, Li et al. 2021) (Table 4). Spatial metrics derived from landscape ecology might fail to comprehensively cover urban form characters (Vanderhaegen and Canters 2017). To avoid this limitation, in this study, the rationale for selecting the urban form character indicators was as follows: (1) to cover urban form characters in three scales: building, street network, and urban block, and (2) to include general ("ontological") categories of indicators: complexity, shape, intensity, connectivity, and dimension (Fleischmann et al. 2021b). We included indicators of urban form character for individual buildings located within an urban block because, following Vanderhaegen and Canters (2017), "individual building characteristics contribute most to urban form at block level". In

Table 2. Description of data sources.

Information	Case-study cities	Data source	Comments
Urban green spaces	All	Urban Atlas, Street Tree Layer, European Settlement Map from Copernicus; OpenStreet Map	Data for 2012 (Urban Atlas), 2011–2013 (Street Tree Layer) 2010–2013 (European Settlement Map) and 2017 (OpenStreet Map); Urban Atlas contains objects of at least 0.25 ha; Street Tree Layers were based on SPOT 5 Supermode data also used for the Urban Atlas; European Settlement Map was based on SPOT5 and SPOT6 satellite imagery with a spatial resolution of 2.5 m
Spatial distribution of residential buildings	Barcelona	Barcelona's City Hall Open Data Service	Data for 2012
	Halle	Land and property register	Data for 2012
	Lodz	Land and property register	Data for 2012 obtained from the data set for 2018 by eliminating all buildings erected after 2012
	Oslo	Land and property register	Data for 2014
	Stockholm	GDS Property Map from Lantmateriet	Data for 2012 obtained from the data set for 2017 by eliminating all buildings erected after 2012
Street network	All	OpenStreet Map	Data for 2017; street network without roads that are not used by pedestrians (motorways, trunks, primary and secondary roads)

addition, we used the indicators for the street network because the urban form is shaped by the configuration of streets in space (Boeing 2018, Lang et al. 2020).

We omitted land use cover, which is also considered in quantitative studies on urban form (Fleischmann et al. 2021b), because it refers to UGS. This could further lead to a UGS-driven identification of urban structures. Similarly, Olivera (2021) omitted social, economic, and environmental aspects from the quantification of urban form characters to correlate them with urban structures. We calculated indicators of urban form characters for buildings and urban blocks in ArcGIS 10.5 using ZonalMetrics (Adamczyk and Tiede 2017) and V-LATE (Lang and Tiede 2003) Toolboxes. The indicators for the street network were calculated in Python using the OSMnx package (Boeing 2017).

To reduce the complexity and correlation of urban form character indicators, we conducted principal component analysis (PCA) (Arrenberg 2020). The PCA enabled us to obtain uncorrelated synthesized indicators of urban form, which captured a high degree of the variance contained in the original set of data in fewer indicators. These synthesized indicators described the urban form of each urban block. We conducted the PCA separately for each city as the interrelation between indicators of urban form may be city-specific. We employed Kaiser's criterion to select the number of principal components that represent synthesized indicators of urban form, choosing only principal components with eigenvalues higher than one. To optimize the statistical performance of the PCA, we used a varimax orthogonal rotation of eigenvectors, which additionally ensures that the results are interpretable.

Identifying urban structures

We applied a two-step cluster analysis (Arrenberg 2020) for synthesized indicators of urban form, approximated by the principal component (factor) scores as the output from the PCA. Using two-step cluster analysis, we identified urban structures as the groups of urban blocks that are homogeneous in terms of urban form characters. The urban blocks that belonged to one cluster were interpreted as one urban structure. Such an urban structure could be described by urban form characters using average values of the synthesized or raw indicators. Any two different urban structures (clusters from the cluster analysis) should differ in the indicators of urban form characters. Each urban block must belong to one cluster only. We did not pre-define the total number of urban structures and allowed the two-step cluster analysis to select the optimum number based on the Akaike Information Criterion. To validate the division of urban blocks into urban structures, we used the Silhouette coefficient of the cluster's cohesion and separation (Arrenberg 2020). We conducted the PCA and two-step cluster analysis in IBM SPSS Statistics 25.

Quantifying disparities in the provision of urban green spaces in accordance with the urban structures

We quantified the disparities in UGS provision using the median and interquartile range of UGS provision in the service area of 300 m around each residential building. We used the medians and interquartile ranges rather than means and standard deviations as they are more robust measures of central tendency and variability due to the non-normal and highly skewed frequency distributions of the UGS provision measures for high spatial resolution data (Tan and Samsudin 2017). Also, we calculated the percentage of residential buildings with UGS provision in a service area of 300 m higher than 10%. We applied Mood's median test (Desu and Raghavarao 2019) to compare the medians of UGS provision in urban structures and to check for disparities between those urban structures.

RESULTS

The results are presented in order, consistent with the steps of our analysis (see "Methods" for the list of steps). First, as the output of the first step of our analysis, we present the classification of UGS using the share of UGS area in the city's total area. Next, we provide results of the provision of UGS categories, quantified at the level of residential buildings for the whole city. This corresponds to the second step of our analysis. Then, we presented the urban structures identified in each case-study city as the

Table 3. Potential physical accessibility of UGS categories.

Name of the UGS category	Potential physical accessibility ensured by the actors with the greatest impact on UGS management
Forests Urban forestry areas (not classified as forests) Green urban areas Trees in urban parks Greenery other than tree canopy in urban parks Trees accompanying roads and transportation areas	High physical accessibility UGS are accessible to all inhabitants; accessibility is ensured by public institutions such as city council or local planning authority through local zoning plans
Greenery other than tree canopy in allotment gardens Trees in allotment gardens Greenery other than tree canopy in cemeteries Trees in cemeteries Greenery other than tree canopy in sports and leisure green areas Trees in sports and leisure green areas	Medium physical accessibility UGS are accessible to a given group of inhabitants, or all inhabitants but with limitations; accessibility is ensured mostly by allotment garden councils, urban green space authorities, city councils etc.
Trees on private land and inner court trees Other greenery on private land and inner court greening Arable land, permanent crops, pastures and wetlands Trees in industrial and commercial areas Other greenery in industrial and commercial areas Trees accompanying railway areas Trees on mineral extractions Trees on construction sites Brownfield trees	Low physical accessibility Accessibility of UGS is limited to individual owners who may—but do not have to—ensure UGS accessibility

output of steps three to six. We end with the results for the inequalities in UGS provision for different urban structures as the output of the seventh step of our analysis.

Urban Green Space Coverage

We quantified the UGS coverage separately for each level of potential accessibility and summarized it using four indicators (Table 5 and Append. 2). The results show that, even when UGS coverage is high in a given city, a large share of UGS might be characterized by limited physical accessibility. In Barcelona, highly and lowly accessible UGS represent 18% and 12% of the total city area, respectively. Other cities noted larger differences in the percentage of UGS in the total area of the city (indicator A). In Halle and Lodz, UGS of low potential physical accessibility have the largest share in the city area—47% and 51%, respectively—whereas UGS of high potential accessibility account for 16% and 15% only. Only in Oslo, due to the omitted public transport, does the share of UGS that is characterized by potentially high physical accessibility account for a much higher share of the city area (56%) than UGS whose accessibility is low (15%).

In each city, the highly accessible UGS mainly consist of tree canopy, whereas lowly accessible UGS are dominated by grass cover. The share of highly accessible tree canopy in the total area of tree canopy in a city varies from 65% (Halle) to 92% (Oslo). In contrast, the share of highly accessible grass cover in its total area is scarce—from 2–3% (Halle, Lodz, Oslo) to 13% and 21% for Barcelona and Stockholm, respectively. This division is closely linked to the physical accessibility of particular UGS categories.

In all cities, the main source of highly accessible UGS is forests (Append. 2). Forests cover 11–12% of the city area in Barcelona, Halle, and Lodz, and 54% of Oslo. In Stockholm, forests and urban forestry areas (not classified as forests) cover 20% of the city area. Depending on the city, UGS of medium physical accessibility mainly consist of allotment gardens (Halle, Lodz) and UGS in sports and leisure spaces (Barcelona, Oslo, Stockholm). The dominant lowly accessible UGS types are those on private land, inner courtyard greenery, agricultural land, and those in industrial and commercial areas. In Oslo and Stockholm, the share of UGS on private land in the city area is higher than the share of other UGS categories characterized by low physical accessibility—7.5% and 13.3%, respectively. In Halle and Lodz, the shares of private land are similar (8.3% and 10.9%). However, in these two cities, the dominant lowly accessible UGS is agricultural areas. In Halle, its share in the total city area is 34.3%, whereas in Lodz, it is 36.4%. In summary, the results show between-city variation in UGS structure and differences in UGS potential physical accessibility.

The Spatially Explicit Provision of Urban Green Spaces

Table 5 summarizes the results for UGS provision based on potential physical accessibility and differentiation between tree canopy and other greenery. A detailed provision of each UGS category is presented in Append. 2.

Again, the between-city variation in UGS provision is visible, especially for highly and lowly accessible UGS. For example, the median percentage of lowly accessible UGS in the service area of 300 m differs between cities, from 4% in Barcelona to 39% in Oslo. The median provision of highly accessible UGS is similar in Barcelona (0.85%) and Lodz (1%), as well as in Halle (1.4%) and Oslo (1.5%). The between-city differences are even greater when we compare the share of residential buildings with more than 10% of UGS in their service areas. For example, in Stockholm, the share of buildings characterized by >10% provision of highly accessible UGS is 55%. In contrast, in Oslo, Halle, and Lodz, it is 21–23%, whereas in Barcelona, it is only 11%.

Table 4. Indicators of urban form characters.

Scale	Category	Definition	Literature
Residential building	Dimension	Mean area of residential buildings	Fleischmann et al. 2021b
	Shape	Mean fractal dimension index for residential buildings	Ma et al. 2020
	Intensity	Edge density for residential buildings	Weber et al. 2014
	Spatial distribution	Average Euclidean nearest-neighbor distance for residential buildings	Fleischmann et al. 2021b
	Connectivity	Percentage of shared edges in total edge length	Wu and Murray 2008
Street network	Dimension	Average street segment length*	Boeing 2017
	Shape	Average circuity, the ratio of network distances to straight-line distances*	Boeing 2019
	Spatial distribution	Average closeness centrality*	Boeing 2018
	Intensity	Street density*	Boeing 2017
	Connectivity	Weighted average clustering coefficient*	Boeing 2018
Urban block	Dimension	Urban block area	Annunziata and Garau 2021
	Shape	Fractal dimension index for urban block	Zhang et al. 2019
	Spatial distribution	Squared Euclidean distance between urban block and its neighbors in terms of building density**	Fleischmann et al. 2021b
	Intensity	Number of residential buildings per urban block area	Oliveira et al. 2020
	Connectivity	Number of adjacent urban blocks	Hermosilla et al. 2014

*Streets in a buffer of 200 m around urban block.
**We referred to continuity as spatial distribution feature and assumed that the more similar are neighboring urban blocks, the more contiguous is urban space.

The results show that the general information on UGS coverage is not enough to capture the provision of UGS, especially if differences in physical access to UGS are taken into account. For example, Oslo, which is characterized by UGS coverage equal to 73% (Table 1), has almost eight times lower provision of highly accessible UGS than Stockholm, which has a lower UGS coverage (50%). This is mainly due to the location of the "Oslomarka" peri-urban forest which is protected against residential development, concentrating densification to the urban built zone between the coastline and the forest.

The provision of tree canopy and other greenery is not the same in each of the five case-study cities. The provision of tree canopy is much lower when only highly accessible UGS are taken into account. The lowest difference between the median provision of highly and lowly accessible tree canopy is observed in Stockholm. In comparison, the median provision of greenery other than tree canopy is much lower when only highly accessible UGS are considered, and this corresponds to a low share of such UGS that is only around 0.4–3% of the city's areas. Similarly, the median provision of other greenery might be limited due to potential restrictions in physical accessibility observed for UGS, for example arable land and private gardens. Interestingly, in each case-study city, these two categories of UGS are characterized by the highest median provision for residential buildings among all UGS categories (Append. 2).

The provision of UGS varies within each city among residential buildings. This is captured by the high values of the interquartile range and could be interpreted as a signal that UGS provision is unevenly distributed among residential buildings in each city. Also, the highly skewed distributions of UGS provision for residential buildings reveal the high disparities in UGS provision between residential buildings, indicating the need to consider more deeply within-city differences in UGS provision.

Extraction and Description of Urban Structures

For each case-study city, we obtained urban blocks with at least one residential building using the extended street network. The numbers of blocks were 4,421 (Barcelona), 969 (Halle), 2,148 (Lodz), 1,059 (Oslo), and 3,474 (Stockholm). We described these urban blocks using 15 indicators of urban form characters (Table 4) and then used them as input data in the PCA. In each case-study city, the PCA yielded five synthesized indicators of urban form characters. The exception is Halle, for which four synthesized indicators of urban form character were extracted from the PCA (see Append. 3 for details). The synthesized indicators of urban form characters explain around 60% of the variability of information from the original data sets.

In line with our expectations (see "Quantifying urban form characters"), the results of the PCA show that the indicators of urban form characters are related, especially the indicators of the street network. For example, in Barcelona, synthesized indicator 5, obtained from the PCA (Append. 3), reflects the shape and intensity of the street network. In Halle, synthesized indicator 4 combines the dimension, intensity, and connectivity of the street network and the urban block shape. Similarly, in Oslo, synthesized indicator 2 is based on the spatial distribution, intensity, and connectivity of the street network and the urban block shape. These synthesized indicators of urban form characters show that the urban block shape is linked to the structure of the street network around such an urban block.

The two-step cluster analysis, which is based on the synthesized indicators of urban form characters, grouped the urban blocks into different urban structures. The total number of urban structures delimited in each city is similar and equals three (for Halle and Stockholm), four (for Barcelona) and five (for Lodz and Oslo). For each two-step cluster analysis, the Silhouette coefficient of the cluster's cohesion and separation was at least 0.4; thus, the urban structures are of sufficient quality. The urban structures are presented in Figs. 2–6.

A detailed characterization of each urban structure can be based on the mean values of synthesized indicators. However, this would require an additional interpretation of each principal component from the PCA, separately for each city. Instead, we provided a general description of the identified urban structures based on the mean values of the three raw indicators of urban form character (Table 6).

Table 5. Urban green space (UGS) provision in the five case-study cities (in %)

UGS and physical accessibility	Indicator	Barcelona	Halle	Lodz	Oslo	Stockholm
High physical accessibility (total)	A	17.80	16.20	14.90	56.40	26.50
	B	0.85	1.40	0.99	1.49	11.59
	C	3.52	8.60	7.94	8.01	17.37
	D	11.31	23.08	21.21	22.46	55.11
Other greenery	A	1.70	1.10	1.00	0.40	3.30
	B	0.00	0.00	0.00	0.00	0.73
	C	0.12	1.09	0.44	0.23	2.87
	D	1.04	3.03	2.31	1.35	3.02
Tree canopy	A	16.10	15.10	13.90	56.00	23.20
	B	0.72	1.08	0.71	1.33	9.45
	C	2.51	5.95	5.07	6.56	15.45
	D	8.52	17.11	16.63	19.61	48.12
Medium physical accessibility (total)	A	3.60	6.9	4.20	2.00	5.10
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	4.74	0.00	0.00	1.25
	D	2.87	15.48	6.17	6.00	6.20
Other greenery	A	3.30	4.90	2.30	1.50	3.40
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	2.76	0.00	0.00	0.71
	D	2.69	10.24	2.69	4.86	4.04
Tree canopy	A	0.30	2.00	1.90	0.50	1.70
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	1.95	0.00	0.00	0.05
	D	0.00	8.68	1.51	0.86	1.22
Low physical accessibility (total)	A	12.30	46.70	50.70	15.10	18.80
	B	3.96	29.90	34.14	38.64	32.29
	C	6.27	24.17	28.47	19.57	22.30
	D	20.39	88.15	92.77	92.48	87.38
Other greenery	A	8.40	40.60	46.00	11.00	9.20
	B	0.00	13.09	13.53	16.35	18.91
	C	2.53	19.41	22.94	17.27	15.28
	D	9.03	59.75	60.30	68.47	77.56
Tree canopy	A	3.90	6.10	4.70	4.10	9.60
	B	2.78	14.36	17.62	18.45	12.31
	C	3.85	10.16	10.15	13.39	11.17
	D	9.35	70.34	83.85	80.83	61.93

A - Percentage of UGS in the total area of the city (in %); B and C - Median (B) and interquartile range (C) of UGS provision in the service area of 300 m around each residential building; D - Percentage of residential buildings with UGS provision in the service area of 300 m greater than 10% (in %).

The results from the two-step cluster analysis show similarities and differences between our case study cities located across Europe. What Barcelona, Halle, Lodz, and Oslo have in common is the division of the cities into core part and suburbia, represented by different urban structures. The central parts of Lodz and Halle are represented by urban structure 1. In Lodz, in particular, this urban structure corresponds to the mainly high-density, historic city center. In Halle, the limited number of urban structures obtained in the two-step cluster analysis results in a sharp division into a high-density central city area and suburbia. By contrast, Lodz is delimited into more urban structures, and so the core-suburbia gradient involves more steps. In Lodz, structures 2 and 3 could be described as areas with mixed residential and commercial functions.

Fig. 2. Urban structures in Barcelona (number of urban blocks in brackets).

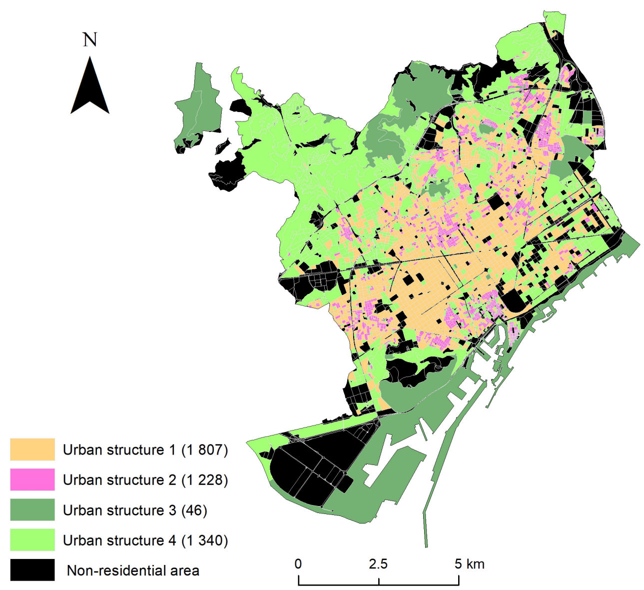
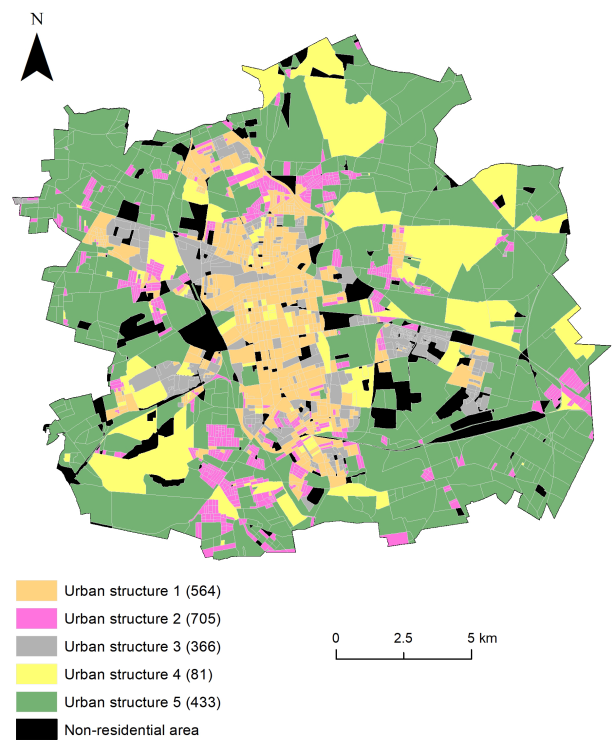
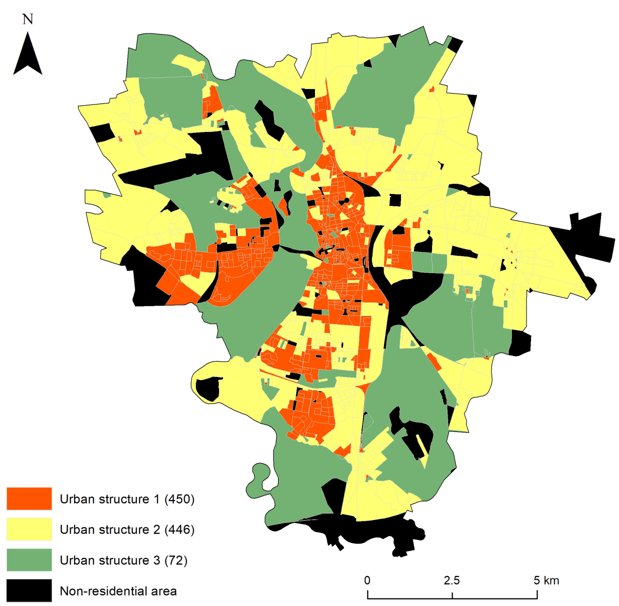


Fig. 3. Urban structures in Lodz (number of urban blocks in brackets).



In Oslo, the division of the city into urban structures is the most concentric of all the case-study cities. The central part of the city mainly features urban structures 1 and 2, encircled by urban structure 3. Urban structures 4 and 5 form the most peripheral part of the city. This is also true of Barcelona, where urban structures 1 and 2 are characterized by a lower mean Euclidean distance between neighboring residential buildings and smaller urban block sizes than urban structures 3 and 4 (Table 6). This means that the density of residential buildings in these urban structures is high. What both Oslo and Barcelona have in common is an urban development area concentrated between a protected peri-urban forest and a coastline and a port area.

Fig. 4. Urban structures in Halle (number of urban blocks in brackets).



Urban structures 4 and 5 in Oslo, 2 and 3 in Halle, 3 and 4 in Barcelona, and 4 and 5 in Lodz represent suburbia, dominated by single-family houses rather than multi-family dwellings. What they have in common is the high size of the urban blocks and the distance between residential buildings, further suggesting low building density. In summary, the results show variation in the urban structures, which could be related at a general level to the historical background of the cities and their land use dynamics. Interestingly, in Stockholm, the urban structures are mixed and do not constitute a continuous area with the same urban structure. In contrast to the other cities, in which the division into urban structures visually suggests a concentric zone model, a visual inspection of the urban structures for Stockholm suggests a multiple nuclei model of the city's spatial development. This is partly an effect of the slightly complicated geography of Stockholm with several islands and waterways.

Fig. 5. Urban structures in Oslo (number of urban blocks in brackets).

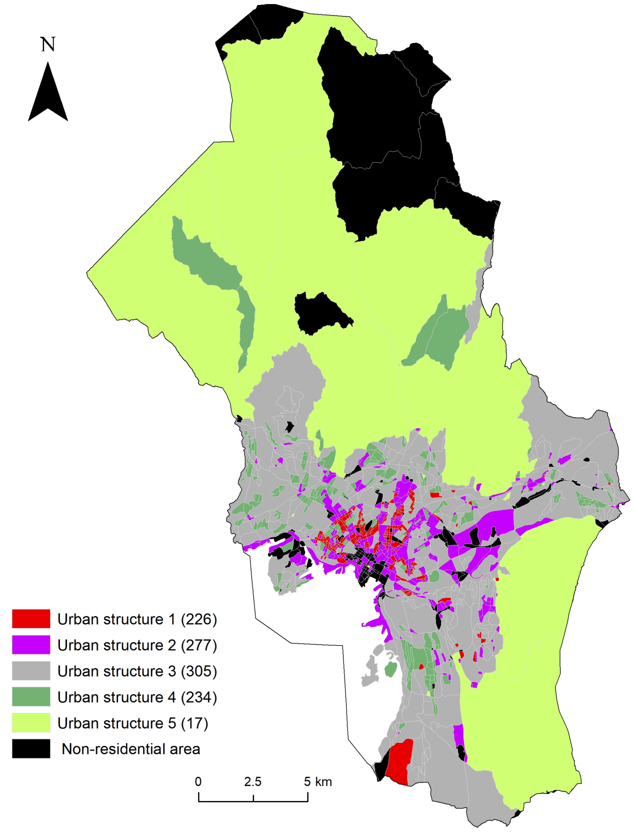


Table 6. Characterization of urban structures in case-study cities

Urban structure	Indicator of urban form character	Barcelona	Halle	Lodz	Oslo	Stockholm
Urban structure 1	A	0.34	1.65	2.81	0.66	10.03
	B	0.04	0.04	0.06	0.07	0.04
	C	1.31	4.23	5.88	2.64	3.71
Urban structure 2	A	0.05	2.71	7.90	18.32	0.86
	B	0.09	0.03	0.03	0.06	0.06
	C	0.46	12.26	2.65	6.55	1.43
Urban structure 3	A	64.21	16.75	15.33	6.47	36.93
	B	0.90	0.05	0.07	0.04	0.05
	C	40.70	63.59	5.38	35.36	19.05
Urban structure 4	A	7.68		20.29	9.11	
	B	0.07		0.04	0.03	
	C	2.56		52.53	10.47	
Urban structure 5	A			24.88	105.36	
	B			0.02	0.04	
	C			36.68	1 409	

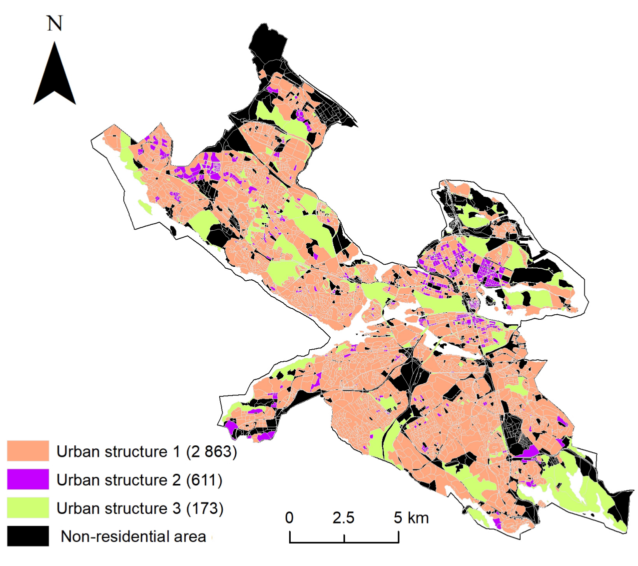
A - The mean Euclidean nearest-neighbor distance for residential buildings (in m); B - The mean street network density in urban block (in m/m²); C - The mean urban block size (in ha).

Disparities in the Provision of Urban Green Spaces in Different Urban Structures

Table 7 shows the median provision of UGS in different urban structures. Mood's median test has a p value < 0.01 for each UGS, confirming statistically significant disparities between urban structures in UGS provision. These differences are observed in each city and for each level of UGS physical accessibility. This further extends the general findings regarding the disparities observed between European cities and the limited physical access to the various UGS categories. The results show that UGS provision for different levels of potential physical accessibility depends on the type of urban structure (Table 7).

In general, in each city and urban structure, there is a similar variation of UGS provision related to the level of physical accessibility. Interestingly, in all cities, the lowest provision is noticed for UGS characterized by medium physical accessibility, which is the result of the small number of those UGS in cities (see Table 5). Also, in each urban structure, the median provision of lowly accessible UGS is much higher than the median provision of highly accessible UGS. The only exception is urban structure 3 in Barcelona, with a median provision of highly and lowly accessible UGS in the service area of 300 m around residential buildings, both of around 10%. In addition, in all cities, except Stockholm, the median percentage of highly accessible UGS in the service area of residential buildings is not higher than 10%.

Fig. 6. Urban structures in Stockholm (number of urban blocks in brackets).



What is also common for our case-study cities, excluding Stockholm, is the lower median provision of UGS in those urban structures that reflect the city's core, and a higher median provision of UGS in the urban structures that correspond to the city's suburbia. For example, in Barcelona, the median provision of UGS for urban structures 1 and 2 (the central part of the city) is around 5–6%, whereas for urban structures 3 and 4 (suburbia), it is 30–37%. Similarly, the central part of Lodz (urban structure 1) is characterized by the lowest median provision of UGS among urban structures in this city. The median percentage of UGS cover in the service area of 300 m around residential buildings for Lodz's central part is 30%. This value rises for urban structures 2 and 3, which correspond to mixed residential and commercial functions (37 and 45%). However, the highest median provision of UGS is observed for urban structures 4 and 5, which represent the outskirts (46 and 70%, respectively). Similar growth of the median provision of UGS in a city's core–suburbia gradient is noticed in Oslo. The results for Stockholm are the exception. In particular, the median provision of UGS does not vary much across the three urban structures.

Despite the above, there are differences between and within cities, mainly in the disproportion between the median provision of lowly accessible tree canopy and other greenery. In the case of highly accessible UGS, in all urban structures and cities, we observe a higher median provision of tree canopy than other greenery. This is not observed for lowly accessible tree canopy and other greenery, however. For example, in Halle, only in urban structure 1 (city center) is the median provision of lowly accessible tree canopy higher than other greenery. In two other urban structures, the median provision of tree canopy and other greenery is almost equal. Similar equalization is observed for the outskirts (urban structure 4) of Barcelona. This contrasts with Lodz and Stockholm. The former notices higher median provision of other greenery (39%) than tree canopy (17%) in the outskirts (urban structure 5). The latter is characterized by a higher median provision of other greenery (21%) than tree canopy (13%) for urban structure 1.

In summary, the results demonstrate that the disparities in the median provision of UGS vary across urban structures. Also, without further consideration of potential physical accessibility and division into vegetation structure, the provision of UGS gives only general information on UGS-related inequalities.

DISCUSSION

The results refer to multiple challenges discussed by urban ecologists and planners. In particular, we propose linking UGS provision at the spatial level of residential buildings and urban structures delimited based on urban blocks, further contributing to the broader discussion on the proper spatial (dis)aggregation of data when analyzing disparities in UGS provision. We also propose considering different levels of potential physical accessibility of UGS when quantifying UGS provision for various urban structures. This further contributes to the ongoing discussion on the role of institutions (e.g., property rights) and infrastructures (e.g., landscape composition) in the flow of benefits from UGS to urban inhabitants. In the broader sense, our findings contribute to the discussion on integrating an analysis of social-ecological systems and urban morphology.

Multiple Spatial Scales and the Quantification of Urban Green Space Provision

We argue for a better understanding of the oversimplifications of findings regarding disparities in UGS provision, which are the result of using spatially aggregated data. In particular, we have demonstrated that UGS provision quantified at a city scale, without considering spatially disaggregated units such as urban structures, provides only general and often overestimated information on UGS provision. Our results show that the lower

Table 7. Median provision of urban green spaces in urban structures (in %) and interquartile range in brackets.

UGS and potential physical accessibility	Urban structure	Barcelona	Halle	Lodz	Oslo	Stockholm
UGS (total)	1	5.61 (8.28)	26.77 (25.71)	30.00 (24.88)	23.02 (22.19)	52.58 (19.17)
	2	4.69 (7.84)	45.82 (23.12)	44.89 (20.20)	27.96 (25.02)	41.02 (40.06)
	3	37.45 (58.46)	49.98 (21.28)	36.52 (15.20)	48.37 (16.73)	57.38 (18.37)
	4	30.01 (41.93)		46.53 (39.78)	48.82 (14.51)	
	5			69.94 (29.99)	50.78 (20.05)	
High physical accessibility (total)	1	0.73 (2.76)	3.40 (10.63)	0.90 (6.32)	1.69 (9.15)	11.46 (17.20)
	2	0.54 (2.32)	0.81 (5.95)	1.08 (7.81)	0.97 (4.87)	11.20 (16.11)
	3	9.66 (27.19)	3.39 (14.83)	2.25 (8.54)	1.59 (8.60)	16.84 (22.63)
	4	3.84 (14.43)		1.06 (9.57)	1.01 (1.80)	
	5			0.69 (9.91)	5.29 (18.91)	
Other greenery	1	0.00 (0.06)	0.41 (2.74)	0.00 (0.97)	0.00 (1.07)	0.85 (3.02)
	2	0.00 (0.11)	0.00 (0.34)	0.00 (0.40)	0.00 (0.57)	0.30 (2.32)
	3	0.00 (0.57)	0.00 (1.83)	0.38 (3.27)	0.00 (0.25)	0.58 (2.51)
	4	0.00 (0.51)		0.00 (0.31)	0.00 (0.00)	
	5			0.00 (0.00)	0.00 (0.00)	
Tree canopy	1	0.66 (2.15)	2.36 (6.97)	0.62 (3.26)	1.43 (7.76)	9.12 (15.04)
	2	0.50 (1.58)	0.73 (4.01)	0.79 (5.15)	0.83 (3.96)	9.72 (15.29)
	3	6.74 (26.05)	2.08 (10.86)	0.89 (3.18)	1.40 (6.92)	14.43 (20.10)
	4	2.87 (11.03)		0.82 (6.21)	0.95 (1.63)	
	5			0.61 (8.72)	4.34 (18.26)	
Medium physical accessibility (total)	1	0.00 (0.00)	0.00 (2.81)	0.00 (0.04)	0.00 (0.67)	0.00 (1.23)
	2	0.00 (0.00)	0.00 (5.52)	0.00 (0.00)	0.00 (0.00)	0.00 (1.49)
	3	0.00 (0.00)	0.00 (5.66)	0.00 (0.95)	0.00 (0.00)	0.00 (0.81)
	4	0.00 (0.00)		0.00 (0.00)	0.00 (0.00)	
	5			0.00 (0.00)	0.00 (0.00)	
Other greenery	1	0.00 (0.00)	0.00 (1.50)	0.00 (0.02)	0.00 (0.50)	0.00 (0.66)
	2	0.00 (0.00)	0.00 (3.25)	0.00 (0.00)	0.00 (0.00)	0.00 (0.92)
	3	0.00 (0.00)	0.00 (3.17)	0.00 (0.50)	0.00 (0.00)	0.00 (0.45)
	4	0.00 (0.00)		0.00 (0.00)	0.00 (0.00)	
	5			0.00 (0.00)	0.00 (0.00)	
Tree canopy	1	0.00 (0.00)	0.00 (0.85)	0.00 (0.00)	0.00 (0.00)	0.00 (0.06)
	2	0.00 (0.00)	0.00 (2.58)	0.00 (0.00)	0.00 (0.00)	0.00 (0.02)
	3	0.00 (0.00)	0.00 (2.31)	0.00 (0.00)	0.00 (0.00)	0.00 (0.02)
	4	0.00 (0.00)		0.00 (0.00)	0.00 (0.00)	
	5			0.00 (0.00)	0.00 (0.00)	
Low physical accessibility (total)	1	3.57 (4.55)	14.44 (16.82)	22.24 (19.25)	12.68 (15.97)	34.26 (20.83)
	2	2.93 (3.92)	34.67 (21.02)	37.25 (19.24)	19.41 (24.55)	22.21 (29.59)
	3	10.02 (27.63)	34.73 (23.81)	28.43 (11.85)	40.48 (14.97)	33.83 (19.70)
	4	17.31 (26.73)		32.93 (33.89)	44.59 (14.54)	
	5			58.83 (35.16)	37.99 (15.56)	
Other greenery	1	0.87 (1.86)	3.04 (11.27)	5.79 (10.40)	4.22 (7.91)	20.63 (14.07)
	2	0.66 (1.44)	16.15 (18.27)	15.33 (13.25)	5.28 (12.48)	10.66 (16.05)
	3	3.88 (17.91)	17.97 (20.19)	8.32 (7.85)	19.02 (16.48)	19.38 (15.69)
	4	7.48 (16.16)		14.04 (28.53)	20.18 (17.27)	
	5			39.18 (40.41)	15.48 (12.70)	
Tree canopy	1	2.56 (2.88)	9.41 (7.83)	14.66 (10.14)	7.44 (6.84)	12.96 (10.27)
	2	2.24 (2.42)	16.21 (10.11)	20.75 (8.24)	11.48 (12.03)	8.88 (14.34)
	3	5.06 (8.49)	14.62 (7.99)	18.87 (8.46)	19.45 (11.80)	12.17 (10.32)
	4	8.56 (8.63)		16.19 (10.25)	22.51 (13.74)	
	5			17.40 (10.85)	20.69 (9.58)	

the spatial level of data aggregation, the more heterogeneous the UGS provision.

Based on our results, in each case-study city, we can observe that the variability of UGS provision (which results from differences between urban structures) is further complicated and nuanced due to the high inequalities in the provision of UGS between residential buildings (see the values of the interquartile range in Table 7). This is in line with previous studies, which suggested that using the proper spatial data scale affects the outcomes of any analysis of UGS disparities (Tan and Samsudin 2017, Rüttenauer 2018, Schaeffer and Tivadar 2019). The smaller the spatial scale, the more detailed the picture of the disparities in UGS provision. The disparities in UGS provision noticed at the microscale may be higher (due to the relatively higher spatial data variability) than disparities measured at a higher spatial scale (Łaszkiewicz et al. 2021, Carvalho et al. 2022). Our results confirm this rule and highlight the need to link conclusions from various spatial data aggregation levels.

We found that the provision of UGS differs among urban structures. This is visible especially when we compare the results for the urban structures that reflect the core city area with those for suburbia. Furthermore, the highly uneven spatial distribution of UGS between city centers and green suburbia does not necessarily correspond to where people live. This is visible in each of our case-study cities, except for Stockholm. For example, in Barcelona, the median provision of UGS for urban structure 4, which corresponds to the city's suburbia, is five times higher than for urban structure 1, which reflects the city center. In Halle, Lodz, and Oslo, the median provision of UGS in suburbia is around two times higher than in those cities' centers. Similar results on the differences between the central and peri-urban areas in UGS accessibility were obtained by others using big geodata (Ma et al. 2020, Chen et al. 2020). Through this study, we propose quantifying UGS provision using spatially explicit data and linking it further with urban structures to improve the understanding of UGS distribution. Analyzing disparities in UGS provision through the lens of urban morphology and using properly selected spatial scales could improve the mapping of UGS supply and demand (Whitehand 2017, 2019, Pauleit et al. 2019).

We are aware that the indicators of urban form characters are not purely independent of each other and might overlap (Fleischmann et al. 2021b). In particular, when it comes to the street network, the assignment of an indicator to a given category, such as connectivity, intensity, or spatial distribution, is vague, and there is no consistency in the literature as to which category such indicators represent. For example, Boeing (2018, 2019) suggested that an average closeness centrality and weighted average clustering coefficient indicate both connectivity and spatial distribution of the street network. Moreover, he argued that those two indicators, as well as average circuity, are measures of street network complexity that are potentially interchangeable. Also, following Fleischmann et al. (2021b), the meaning of spatial distribution is broad as it may reflect distance, continuity, or concentration of buildings or urban blocks. However, distance-based indicators used to capture the spatial distribution of buildings might correlate with measures of building connectivity. Although Fleischmann et al. (2021b) assigned connectivity indicators only to street networks, we have also added indicators of connectivity for buildings and urban blocks. This might also result in the correlation between indicators.

The Physical Accessibility of Urban Green Spaces

Our results contribute to the emerging need for a deeper consideration of the potential limitation in gaining benefits from UGS due to potentially restricted physical accessibility in cities (Biernacka et al. 2020) and barriers (Barber et al. 2021). We demonstrate that, without including UGS diversity and the broader understanding of physical accessibility that goes beyond walking distance metrics (Wolff 2021), analyzing disparities in UGS provision may lead to an oversimplification of the findings. Our results show that high UGS coverage does not guarantee that all inhabitants have UGS in their surroundings.

Even in cities characterized by high UGS coverage, the median provision of UGS provided by highly accessible UGS could be low. Using extensive cross-study spatial analysis, we showed that the discussion on UGS needs to acknowledge and incorporate the diversity of physical accessibility of UGS that shapes the possibility of city inhabitants benefiting from UGS. Our results show that omitting the physical accessibility of UGS in an analysis of disparities in UGS provision may lead to the overestimation of real UGS provision, especially for those benefits provided by UGS that are highly dependent on the physical accessibility of UGS, such as active recreation (Biernacka and Kronenberg 2018, 2019).

In particular, we show that a high share of UGS in the total area of a city does not always guarantee that all residential buildings have it in their immediate surroundings. For example, in Oslo, the coverage of potentially highly accessible UGS is much higher than in Stockholm—56% and 26.5%, respectively. However, the median provision of these UGS in the service area of 300 m around residential buildings is much lower in Oslo (1.5%) than in Stockholm (12%). It is even more visible when comparing Oslo and Halle. The medians of UGS provision in the service area of 300 m around each residential building (indicator B in Table 5) are almost the same (around 1.5%), although the cities vary in terms of UGS coverage. When it comes to Oslo, the low median provision of these UGS in the service area of 300 m is partly offset by access to peri-urban nature by public transport, which was not considered in this study.

Our results suggest that the provision of arable land and UGS on private land and inner courtyard greenery, which represent lowly accessible UGS, is the highest among all UGS categories in each case-study city. In Barcelona, half of the residential buildings have a share of those UGS in their service area of 300 m below 3%. This contrasts with the other case-study cities. For example, in Halle and Lodz, the median provision of arable land and UGS on private land and inner courtyard greenery equals 27% and 31%, respectively. Although most of the data supporting our analysis came from 2012, we expect that over the last decade the median provision of UGS in our case-study cities could have decreased due to the replacement of informal UGS by new residential or commercial developments.

The limited physical accessibility of UGS excludes those who do not have property rights from having pleasant, green surroundings for active recreation, such as walking, cycling, or practicing sport (Biernacka and Kronenberg 2019). In the case of arable land, UGS on private land, and inner courtyard greenery, we may expect that at least their private owners, who have those UGS in their service area of 300 m, can gain all of those benefits that require physical contact with greenery. Other city inhabitants, who cannot enter UGS on private plots, can still gain benefits from those UGS related to visual appreciation or air purification, to mention just a few.

The Context of the Mediating Filters Framework

According to the research framework of the three systemic filters, the flows of benefits from UGS to urban inhabitants are mediated by three filters: institutions (e.g., property rights, social norms), infrastructures (e.g., landscape composition), and perceptions (Andersson et al. 2019, 2021). Our results highlight the relevance of two of these filters in particular: institutions and infrastructures.

Institutions reflect policy intentions, social norms, ownership, and user rights. In this study, this filter is represented by the diversified physical accessibility of UGS and reflects institutions (ownership, social norms, and property rights). We included institutions by assigning to each UGS category the potential physical accessibility ensured by actors with the greatest influence on a given UGS, based on the framework proposed by Biernacka and Kronenberg (2018, 2019) and Biernacka et al. (2020).

Our results show that the possibilities of benefiting from UGS could be sharply limited because of changes in UGS accessibility. This could be further interpreted as the impact of institutions that can restrict the potential delivery of benefits from UGS. Our results reflect the sharp between-cities differences in the median provision of UGS, such as those in private land and inner courtyard greenery, which could further provide opportunities for active recreation (Hanson et al. 2021). In Stockholm, the median provision of such UGS is around 18%, in Halle and Lodz, 7% and 5%, respectively, whereas in Barcelona, it is only 1% (see Append. 2). At the same time, UGS on private land and inner courtyard greenery have low physical accessibility, which is limited mainly to the landowners. Such an important impact of UGS accessibility on the provision of cultural UGS-related benefits to city inhabitants could be interpreted as a result of institutional barriers.

Infrastructures are understood as the composition and configuration of the urban landscape that capture the interrelations between supply and demand areas (Andersson et al. 2019, 2021). The present study includes the role of infrastructures twofold—by using the service area to quantify UGS provision at the level of each residential building, and by allowing for the variation of UGS provision in different urban structures. Using the service area for each residential building, we are able to realistically capture whether the inhabitants can reach UGS to gain benefits. This is important, especially when it comes to recreation. We found that the possibility of benefiting from UGS thanks to daily, direct contact with greenery is highly diversified between cities and within them. However, for our study, it was crucial to account for the heterogeneous urban structures, which could be treated as an approximation of infrastructures.

Our results confirm the hypothesis that the median provision of UGS varies among urban structures. This could be further linked with the concept of the spatial production function of UGS benefits (Andersson et al. 2021). In particular, urban structures, as a product of the human–environment interaction, influence the distribution and physical accessibility of UGS and, in the broader context, the delivery of benefits for human wellbeing. According to our results, the urban structures where the human–environment interactions transformed the space to the largest extent (such as in the core city areas) are characterized by the limited provision of UGS. Urban structures that are less transformed by human activity (especially suburbia) have the highest provision of selected UGS. This could further supplement the ongoing discussion on how to manage UGS to support the flow of benefits from UGS to city inhabitants (Sikorski et al. 2021).

Toward an Integrated Social-Ecological Urban Morphology

The need for broader integration of urban morphology and social-ecological systems has been highlighted several times both by urban morphologists (Whitehand 2017, 2019, Marcus et al. 2019) and urban ecologists (Marcus and Colding 2014). As a result, the number of attempts to combine both fields for a broader understanding of social-ecological processes has been growing in recent years (Sharifi 2019, Li et al. 2021, Oliveira 2021). This study contributes to the ongoing discussion on the advantages of such an integration by demonstrating how disparities in UGS provision are shaped by heterogeneous urban structures.

Considered from the morphological perspective, intra-city differences reflect the processes that occur during a city's development, or past and present urban planning decisions, among others. For these reasons, urban planners cannot treat the whole urban area in the same way, as the different parts may not be comparable (Grafius et al. 2018, Oliveira 2021). Accordingly, in this study, we propose "comparing the comparable" and quantifying the inequalities in UGS provision in accordance with differences between urban structures. In addition, we treat the division of cities into urban structures as the approximation of infrastructures as mediating factors that may affect the flow of UGS-related benefits.

Urban form, as a product of human–environment interactions, shapes the spatial distribution of UGS. Our results demonstrate this fact as the differences among urban structures in (1) UGS coverage, (2) the median provision of UGS for residential buildings, and (3) the intensity of disparities in UGS provision. Similar conclusions were reached by others who attempted to link UGS and heterogeneous urban space (Grafius et al. 2018, Marcus et al. 2019). Ossola and Hopton (2018) suggested that urban morphology was one of the main drivers of urban tree cover in Denver, and Zhang et al. (2020b) demonstrated that urban form influenced biomass loss for the Yangtze River Delta cities in China. Our results enable us to draw a similar conclusion. The provision of UGS varies not only between cities but also between different urban structures within each city, which further confirms other findings (Ossola and Hopton 2018, Ossola et al. 2019, Zhang et al. 2020b).

Although we found that the provision of UGS and UGS-related disparities are affected by the urban form of cities, the question of reverse causality arises. In this study, we did not account for land-use patterns when identifying urban structures (see "Quantifying urban form characters"). It does not mean that the urban structures we obtained are not partly affected by UGS. The location of small pieces of UGS within urban blocks, or even the configuration of urban blocks, to mention just a few examples, may affect the indices of urban form characters and indirectly affect the identification of urban structures. This would be in line with Guyot et al. (2021), who proposed including UGS cover in the identification of urban structures. This could further explain the differences in UGS coverage among urban structures. In the broader context, this means reciprocity in the relationship between UGS and urban form.

The importance of urban morphology in the diversification of UGS provision is linked to the spatial distribution of UGS categories. Each UGS category is differently distributed across urban structures, which results in a variation in UGS provision. In other words, within-city configuration determines the spatial distribution of environmental characteristics, which has further implications for UGS (Steele and Wolz 2019). In particular, this is highly visible in the gradient from the city center to the suburbs. Nevertheless, for all urban structures, the provision of potentially highly accessible UGS is much lower than those characterized by low physical accessibility. At the same time, further disaggregation of UGS into tree canopy and other greenery demonstrates that, in a few cases, the provision of potentially highly accessible tree canopy is higher than the median provision of potentially lowly accessible tree canopy.

In the broader context, our results highlight that social-ecological processes are linked to urban morphology, which means that they cannot be analyzed separately. Thus, social-ecological systems could be better understood through the lens of urban morphology. This is in line with the recent literature, which emphasizes human–environment interactions, which result in the social-ecological change expressed by urban morphology. Perhaps then, to better understand social-ecological processes, it would be relevant to continue integrating the knowledge and tools used in landscape ecology and urban morphology (Marcus et al. 2019, Whitehand 2019, Oliveira 2021).

CONCLUSION

This study demonstrates the advantages of linking the disparities in UGS provision with the heterogeneous intra-city urban structures. We applied mixed-methods for multiple spatially explicit data to comprehensively analyze the provision of UGS and their disparities for each residential building in five European cities (Barcelona, Halle, Lodz, Oslo, Stockholm). We linked them to urban structures delimited through the lens of urban morphology, using indices of urban form characters.

Our results show that the general information on UGS coverage is not enough to capture the provision of UGS. Also, physical access to UGS differentiates the amount of UGS in the service area around residential buildings. Even when the UGS coverage is high in a given city, in reality, a large share might be characterized by limited physical accessibility. The results show both between-city and within-city differences in the provision of highly and lowly accessible UGS. This further suggests the need to consider deeply the use of spatially disaggregated data and multiple spatial scales to go beyond general and often overestimated information on the amount of UGS for city inhabitants.

Our findings suggest that the urban structures where the human–environment interaction has transformed the space (such as in the core city areas) are characterized by limited UGS provision. Urban structures that are less transformed by human activity (especially suburbia) have the highest provision of selected UGS. In the broader sense, this means that social-ecological processes and urban form cannot be separated; thus, we advocate linking both. With this study, we support the proposal highlighted by urban morphologists and urban ecologists to support the better understanding of social-ecological systems through the lens of urban morphology and vice versa.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13453

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Data Availability:

Data on the provision of 21 urban green space categories for each residential building are publicly available in the WFS format. Barcelona: https://dservices1.arcgis.com/Y0GEUoQU0oZOJlz6/arcgis/services/Barcelona/WFSServer?service=wfs&request=getcapabilities Halle: https://dservices1.arcgis.com/Y0GEUoQU0oZOJlz6/arcgis/services/Halle/WFSServer?service=wfs&request=getcapabilities Lodz: https://dservices1.arcgis.com/Y0GEUoQU0oZOJlz6/arcgis/services/Lodz/WFSServer?service=wfs&request=getcapabilities Oslo: https://dservices1.arcgis.com/Y0GEUoQU0oZOJlz6/arcgis/services/Oslo/WFSServer?service=wfs&request=getcapabilities Stockholm: https://dservices1.arcgis.com/Y0GEUoQU0oZOJlz6/arcgis/services/Stockholm/WFSServer?service=wfs&request=getcapabilities Other data used in our paper came from open sources listed in Appendix 1, such as OpenStreet Map and Urban Atlas.

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Appendix 1. Multiple-source data on urban green spaces for the case study cities.

Name of the UGS category	Code	Data source and data processing
Urban forestry areas (not classified as forests)	GS4	Green urban areas in UA, intersected with the tree layer from COPERNICUS
Forests	GS5	Forests in UA
Greenery other than tree canopy in urban parks	GS18	Green urban areas in UA, intersected with OSM urban parks
Trees in urban parks	GS16	Green urban areas in UA, intersected with OSM urban parks and with the tree layer from COPERNICUS
Green urban areas	GS8	Green urban areas in UA other than forest urban areas, forests, urban parks, and trees in urban parks
Trees accompanying roads and transportation areas	GS7	Road, rail and associated land in UA (CODE2012 = '12210' OR CODE2012 = '12220' OR CODE2012 = '12400' OR CODE2012 = '12300'), intersected with the tree layer from COPERNICUS
Trees on mineral extractions	GS11	Mineral extractions, dump sites in UA, intersected with the tree layer from COPERNICUS
Trees on construction sites	GS17	Construction sites in UA, intersected with the tree layer from COPERNICUS
Brownfield trees	GS2	Land without current use in UA, intersected with the tree layer from COPERNICUS
Tree canopy in industrial and commercial areas	GS10	Trees in industrial areas: industrial, commercial, military in UA, intersected with the tree layer from COPERNICUS
Greenery other than tree canopy in industrial and commercial areas	GS21	Greenery other than trees: industrial, commercial, military in UA, intersected with green coverage from European Settlement Map
Trees accompanying railway areas	GS6	Road, rail and associated land in UA (CODE2012 = '12230'), intersected with tree layer from COPERNICUS
Tree canopy in private land and inner court trees (e.g., house gardens)	GS9	Trees on private land: urban fabric in UA, intersected with the tree layer from COPERNICUS
Greenery other than tree canopy in private land and inner court greenery (e.g., house gardens)	GS20	Greenery other than trees: urban fabric in UA, intersected with green coverage from European Settlement Map
Arable land, permanent crops, pastures and wetlands	GS19	Arable land (annual crops), permanent crops, herbaceous vegetation, pastures and wetlands in UA
Greenery other than tree canopy in cemeteries	GS3	Green urban areas in UA, intersected with OSM cemeteries

Trees in cemeteries	GS15	Green urban areas in UA, intersected with OSM cemeteries and with the tree layer from COPERNICUS
Greenery other than tree canopy in sports and leisure green areas	GS12	Sport/leisure areas in UA
Trees in sports and leisure green areas	GS13	Sport/leisure areas in UA, intersected with the tree layer from COPERNICUS
Greenery other than tree canopy in allotment gardens	GS1	Sport/leisure areas in UA, intersected with OSM allotment gardens
Trees in allotment gardens	GS14	Sport/leisure areas in UA, intersected with OSM allotment gardens and with the tree layer from COPERNICUS

Appendix 2. Urban green space coverage and its spatially-explicit provision.

UGS and physical accessibility	Indicator	Barcelona	Halle	Lodz	Oslo	Stockholm
High physical accessibility (total)	A	17.80	16.20	14.90	56.40	26.50
	B	0.85	1.40	0.99	1.49	11.59
	C	3.52	8.60	7.94	8.01	17.37
	D	11.31	23.08	21.21	22.46	55.11
Forests	A	12.20	11.20	11.50	54.40	9.60
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	2.91	5.26	10.45	9.62	6.67
Urban forestry areas (not classified as forests)	A	0.90	1.90	0.60	0.80	10.60
	B	0.00	0.00	0.00	0.00	4.32
	C	0.00	0.88	0.04	0.06	12.25
	D	0.57	3.99	1.42	5.18	31.30
Green urban areas	A	1.70	1.10	0.90	0.40	3.30
	B	0.00	0.00	0.00	0.00	0.73
	C	0.12	1.09	0.44	0.23	2.87
	D	1.04	3.03	2.31	1.35	3.02
Trees in urban parks	A	0.90	0.70	1.00	0.20	1.50
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.50
	D	0.58	1.56	2.19	0.47	3.66
Greenery other than tree canopy in urban parks	A	1.30	0.70	0.60	0.30	1.00
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.16
	D	1.24	1.90	0.77	2.17	0.80
Trees accompanying roads and transportation areas	A	0.90	0.50	0.20	0.20	0.60
	B	0.46	0.44	0.20	0.35	0.52
	C	1.06	0.75	0.52	0.90	1.10
	D	0.08	0.00	0.00	0.03	0.01
Medium physical accessibility (total)	A	3.60	6.90	4.20	2.00	5.10
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	4.74	0.00	0.00	1.25
	D	2.87	15.48	6.17	6.00	6.20
Greenery other than tree canopy in allotment gardens	A	0.00	3.00	0.90	0.10	0.50
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.00	5.67	0.73	0.41	0.47
Trees in allotment gardens	A	0.00	0.60	1.40	0.00	0.40
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.00	0.54	1.97	0.00	0.20
Greenery other than tree canopy in cemeteries	A	0.20	0.10	0.50	0.20	0.20
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.21	0.00	0.31	0.35	0.00
Trees in cemeteries	A	0.00	0.60	0.10	0.10	0.60
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.00	1.08	0.10	0.25	0.20
Greenery other than tree canopy in	A	3.10	1.80	0.80	1.30	2.70
	B	0.00	0.00	0.00	0.00	0.73
	C	0.12	1.09	0.44	0.23	2.87

sports and leisure green areas	D	1.04	3.03	2.31	1.35	3.02
Trees in sports and leisure green areas	A	0.20	0.90	0.40	0.30	0.80
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.63	0.00	0.00	0.42
	D	2.46	3.55	1.00	3.97	3.55
Low physical accessibility (total)	A	12.30	46.70	50.70	15.10	18.80
	B	3.96	29.90	34.14	38.64	32.29
	C	6.27	24.17	28.47	19.57	22.30
	D	20.39	88.15	92.77	92.48	87.38
Tree canopy in private land and inner court trees	A	3.30	4.10	3.60	3.60	8.10
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.18	0.00	0.00	0.00
	D	0.00	0.86	0.27	0.14	0.33
Other greenery on private land and inner court greenery	A	3.20	4.20	7.30	3.9	5.20
	B	0.81	7.16	5.45	12.49	17.58
	C	2.21	13.76	10.17	15.89	15.12
	D	6.93	39.20	30.13	58.48	73.46
Arable land, permanent crops, pastures and wetlands	A	3.80	34.30	36.40	6.30	2.90
	B	2.44	12.69	15.86	17.04	11.58
	C	3.46	10.41	10.35	13.49	11.49
	D	7.77	62.29	77.53	76.12	57.87
Tree canopy in industrial and commercial areas	A	0.60	1.60	0.90	0.50	1.30
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	2.45	17.26	0.00	0.00
	D	1.53	18.51	29.88	6.72	2.52
Other greenery in industrial and commercial areas	A	1.30	3.10	2.30	0.80	1.10
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.96	0.63	0.83	0.79
	D	0.12	1.05	0.39	0.84	0.42
Trees accompanying railway areas	A	0.00	0.20	0.10	0.00	0.00
	B	0.00	0.38	0.57	0.19	0.21
	C	0.38	1.84	2.17	1.59	0.96
	D	0.21	1.03	1.58	1.81	0.21
Trees in mineral extractions	A	0.00	0.00	0.10	0.00	0.00
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.00	0.08	0.00	0.00	0.00
Trees in construction sites	A	0.00	0.00	0.00	0.00	0.00
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.00	0.00	0.00	0.00	0.00
Brownfield trees	A	0.00	0.20	0.20	0.00	0.00
	B	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00
	D	0.00	0.05	0.00	0.00	0.00

A – percentage of UGS in the total area of the city [in %]; B and C – median (B) and interquartile range (C) of UGS provision in the service area of 300m around residential building; D – percentage of residential buildings with UGS provision in the service area of 300m higher than 10% [in %].

Appendix 3. The results from PCA.

Barcelona

Category	Scale	Synthesized indicators of urban form characters				
		Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5
Dimension	Residential building	-0.541	0.102	-0.115	0.207	0.156
Shape	Residential building	0.029	0.011	-0.290	0.726	0.030
Intensity	Residential building	0.900	0.171	-0.114	0.038	0.027
Spatial distribution	Residential building	-0.166	-0.147	0.290	0.597	-0.111
Connectivity	Residential building	0.769	-0.020	-0.304	-0.205	-0.050
Dimension	Street network	-0.022	0.138	-0.624	0.095	-0.100
Shape	Street network	0.002	0.099	0.164	-0.094	-0.754
Spatial distribution	Street network	0.377	0.619	0.088	-0.013	0.171
Intensity	Street network	-0.003	0.093	0.194	-0.142	0.581
Connectivity	Street network	-0.045	0.059	0.598	0.037	-0.102
Dimension	Urban block	0.015	-0.750	0.164	0.156	0.029
Shape	Urban block	0.427	0.286	0.609	-0.024	0.128
Spatial distribution	Urban block	0.658	0.086	0.259	0.070	0.117
Intensity	Urban block	0.922	0.148	0.089	0.046	0.038
Connectivity	Urban block	-0.019	-0.838	-0.126	-0.053	0.073

Halle

Category	Scale	Synthesized indicators of urban form characters			
		Indicator 1	Indicator 2	Indicator 3	Indicator 4
Dimension	Residential building	-0.024	-0.046	-0.690	0.261
Shape	Residential building	-0.198	-0.016	0.774	-0.025
Intensity	Residential building	0.757	0.339	0.231	0.229
Spatial distribution	Residential building	-0.512	0.112	0.064	0.058
Connectivity	Residential building	0.782	-0.022	-0.083	0.059
Dimension	Street network	0.249	0.371	0.118	-0.615
Shape	Street network	-0.099	0.218	0.147	-0.002
Spatial distribution	Street network	0.334	0.581	0.064	0.454
Intensity	Street network	0.375	0.233	-0.109	0.715
Connectivity	Street network	-0.147	0.160	0.103	0.366
Dimension	Urban block	-0.091	-0.790	0.155	-0.108
Shape	Urban block	0.316	0.165	-0.058	0.613
Spatial distribution	Urban block	0.274	-0.117	0.620	0.317
Intensity	Urban block	0.643	0.324	0.583	0.194
Connectivity	Urban block	0.017	-0.866	-0.002	-0.092

Lodz

Category	Scale	Synthesized indicators of urban form characters				
		Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5
Dimension	Residential building	0.176	-0.323	0.713	-0.008	-0.140
Shape	Residential building	-0.261	0.416	0.188	-0.192	0.506
Intensity	Residential building	0.498	0.695	0.009	0.109	-0.063
Spatial distribution	Residential building	-0.153	-0.541	0.001	-0.055	0.231
Connectivity	Residential building	0.009	0.858	0.000	0.098	0.030
Dimension	Street network	0.219	-0.102	-0.765	0.002	-0.061
Shape	Street network	0.198	-0.072	-0.292	0.088	0.464
Spatial distribution	Street network	0.778	0.121	0.017	-0.119	0.114
Intensity	Street network	0.438	0.199	0.756	-0.044	-0.051
Connectivity	Street network	0.126	-0.178	0.012	0.081	0.681
Dimension	Urban block	-0.665	-0.148	-0.051	0.304	-0.068
Shape	Urban block	0.637	0.056	0.134	0.018	-0.080
Spatial distribution	Urban block	-0.151	0.055	-0.030	0.874	0.098
Intensity	Urban block	-0.213	0.152	-0.016	0.879	-0.004
Connectivity	Urban block	-0.630	0.015	0.150	0.237	-0.244

Oslo

Category	Scale	Synthesized indicators of urban form characters				
		Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5
Dimension	Residential building	-0.257	0.388	-0.190	0.001	-0.562
Shape	Residential building	-0.039	0.039	-0.016	-0.039	0.692
Intensity	Residential building	0.809	0.333	0.249	-0.164	-0.148
Spatial distribution	Residential building	-0.223	-0.026	0.028	0.625	-0.065
Connectivity	Residential building	0.829	-0.114	-0.193	-0.079	-0.053
Dimension	Street network	0.144	-0.155	0.770	0.126	-0.066
Shape	Street network	-0.010	-0.039	0.054	0.396	0.027
Spatial distribution	Street network	0.260	0.703	0.291	-0.129	-0.233
Intensity	Street network	0.143	0.842	-0.268	-0.132	-0.096
Connectivity	Street network	-0.053	0.375	0.245	0.346	0.170
Dimension	Urban block	0.067	-0.259	-0.261	0.681	-0.068
Shape	Urban block	0.093	0.709	0.115	-0.142	0.096
Spatial distribution	Urban block	0.527	0.321	-0.159	0.130	0.369
Intensity	Urban block	0.846	0.166	0.278	-0.128	0.213
Connectivity	Urban block	0.066	-0.307	-0.608	0.132	-0.133

Stockholm

Category	Scale	Synthesized indicators of urban form characters				
		Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5
Dimension	Residential building	-0.292	0.226	0.038	-0.679	-0.128
Shape	Residential building	0.040	0.064	-0.566	-0.110	0.022
Intensity	Residential building	0.768	0.296	0.180	-0.069	-0.101
Spatial distribution	Residential building	-0.250	-0.086	-0.043	0.039	0.625
Connectivity	Residential building	0.732	-0.030	0.004	-0.137	-0.198
Dimension	Street network	-0.011	0.198	0.043	0.565	-0.468
Shape	Street network	0.072	0.178	0.033	0.108	0.593
Spatial distribution	Street network	0.182	0.655	0.087	0.079	0.106
Intensity	Street network	0.261	0.267	0.602	-0.234	-0.129
Connectivity	Street network	-0.119	0.206	0.062	0.441	0.160
Dimension	Urban block	-0.058	-0.739	-0.115	-0.049	0.124
Shape	Urban block	0.195	0.005	0.826	0.025	0.111
Spatial distribution	Urban block	0.796	0.023	0.079	0.088	0.092
Intensity	Urban block	0.873	0.174	0.094	0.230	-0.025
Connectivity	Urban block	-0.064	-0.695	0.407	0.030	-0.139