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Parks in context: advancing citywide spatial quality assessments of urban green spaces using fine-scaled indicators

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ABSTRACT. Urban green spaces have gained attention because of their increasing relevance to human well-being in the context of challenges related to urbanization and climate change. Detailed, systematic, citywide assessments of specific urban green space characteristics that provide a sufficient understanding of resident interactions with green spaces and respective ecosystem service flows are lacking. We chose the city of Leipzig, one of the fastest growing cities in Germany, as a case study to assess the quality of publicly available green spaces by incorporating spatial context as a key dimension in determining their actual quality. We established 33 indicators that describe (1) natural elements, e.g., the types and configuration of vegetation and the proportion of water bodies; (2) built elements, e.g., various recreational facilities and path density; and (3) the embeddedness of green spaces within the built, social, and natural environment (context), e.g., the number of neighboring residents, nearby green or blue elements, and exposure to traffic. Based on these indicators, we developed a scoring approach that provides an evaluation of green space quality in terms of the potential to provide recreational ecosystem services. We identified and discussed spatial gaps and deficits in the quality of green space supply as well as leverage points for making operational improvements at the individual green space level. Our study provides urban planning guidance for identifying untapped potential for ecosystem services provision, e.g., because of usage barriers, and may help to balance the trade-offs between benefits for citizens and ecology and thus improve green spaces for both people and nature.

Key Words: *context; ecosystem services; green space quality; indicators; Leipzig; OSM; spatial assessment*

INTRODUCTION

Cities worldwide face complex environmental and social challenges arising from urbanization and climate change, including environmental pollution, traffic congestion, heat, loss of green and blue space, and inequities (EEA 2018, IPCC 2018, United Nations 2019). In Europe, climate change has an impact on cities by increasing the frequency and intensity of hot summer days and extreme weather events (EEA 2016, Guerreiro et al. 2018). High levels of air pollution and noise combined with heat island effects result in adverse impacts on human health and well-being (Hartig et al. 2014, Mueller et al. 2017, Zivin and Neidell 2018). The provision of urban green spaces may counteract these negative health impacts (Kabisch et al. 2017). The intersection of health, environmental stressors, and urban green spaces (UGS, hereafter) has gained prominence on the international planning and policy agenda through the United Nations Sustainable Development Goals (SDGs) and the New Urban Agenda. These policy platforms call on cities to become protagonists in ensuring sustainable development by rethinking the way cities are designed and inhabited (Klopp and Petretta 2017, Rodriguez et al. 2018).

Sustainable development is thus linked to UGS and their functions and services, which are essential for mitigating and adapting to urbanization and climate change-induced impacts. Urban green spaces provide multiple ecosystem services (ES, hereafter), e.g., the regulation of air and noise pollution and extreme weather events as well as the provision of space for leisure and recreation (Dobbs et al. 2014, Larondelle et al. 2014, Dickinson and Hobbs 2017, Nowak et al. 2018). Urban green spaces have direct impacts on human well-being and health by promoting physical activities, social interaction, relaxation, and simple enjoyment (Cohen et al. 2007, Konijnendijk et al. 2013, Wheeler et al. 2015, Kabisch et al. 2017). Moreover, UGS serve

as important habitats for hosting and maintaining biodiversity (Melliger et al. 2017, Banaszak-Cibicka et al. 2018).

Urban green spaces may also provide different usage opportunities and values for specific groups of residents with distinct socio-demographic backgrounds and neighborhood contexts (Kabisch et al. 2015, Sallis et al. 2016, Andersson et al. 2019, Keeler et al. 2019). Even at local or regional levels with fairly consistent policy and cultural settings, there is a need to incorporate the spatial and socioeconomic context (surroundings) of UGS as defined by factors such as accessibility or connectivity with residential areas to assess the multitude of factors that may influence the attractiveness and use of UGS and hence the resulting benefits for health and well-being (Voigt et al. 2014, Ekkel and de Vries 2017, Biernacka et al. 2020). To improve the UGS supply in terms of quality and quantity, urban planners need to be highly informed about how existing green spaces are characterized regarding ES provision and infrastructural and contextual aspects (Wolch et al. 2014, Mueller et al. 2017). This becomes particularly relevant for socially inclusive park designs that consider different demographic and cultural groups with specific needs to improve the quality of life in potentially undersupplied neighborhoods and for climate change mitigation and adaptation strategies (Emilsson and Sang 2017, Knight et al. 2018, Flowers et al. 2019).

Nevertheless, the complex nature of urban landscapes remains understudied in terms of providing detailed and differentiated information on the overall quality of UGS, its capacity to provide ES, and how and which people interact with UGS and hence benefit from ES (Niemelä 2014, Kabisch et al. 2015, Wheeler et al. 2015, McPhearson et al. 2016, Dickinson and Hobbs 2017). This might be attributable to the complexity of UGS in providing

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both ecological and social functions and the challenges that arise from the high level of heterogeneity of patterns and processes within the social-ecological system of a city. In urban systems, gray, green, and blue elements are volatile and strongly intertwined and coupled with human interactions. In UGS assessments, this complexity leads to high data requirements (e.g., spatial and temporal resolutions) compared to studies conducted at the broader landscape level. In particular, there is little evidence on how the vegetation structure (including the species composition), infrastructure elements (e.g., sports or play facilities), and the configuration of green spaces within the urban fabric (interrelationships with other urban structure types) affect the actual provision of ES (Pataki et al. 2011, Wheeler et al. 2015, Kremer et al. 2016, Andersson et al. 2019).

Assessments of UGS availability, i.e., the purely quantitative distribution of green space and certain distances to residential areas within a city, have been the subject of numerous previous studies, which have been mostly based on ready-to-use land-cover data with respective limitations, e.g., uncertain data quality (Larondelle et al. 2014, Huang et al. 2017, Smith et al. 2017, Feltynowski et al. 2018). A few studies have made advances in assessing qualitative UGS criteria at a finer scale, including the differentiation of inner structural patterns such as vegetation cover or the availability of playgrounds and benches (Kaczynski et al. 2008, Lehmann et al. 2014, de la Barrera et al. 2016, Dennis et al. 2018). However, such studies rarely examine the broader context within the city, e.g., the surrounding water bodies or the availability of public transport, or consider multiple components of UGS structure, such as natural and man-made elements, at the same time (Giles-Corti et al. 2005, Vaughan et al. 2013, Voigt et al. 2014, Massoni et al. 2018, Biernacka et al. 2020, Vierikko et al. 2020). Studies that have made progress toward assessing the qualitative characteristics of UGS typically assessed only a few exemplary parks within cities or relied on presence-absence scores for green space structural elements, i.e., they only considered whether features such as playgrounds, water bodies, or areas for dogs were present but did not differentiate them by extent, quantity, or quality (Taylor et al. 2011, Voigt et al. 2014, Massoni et al. 2018, Biernacka et al. 2020).

Standardized indicators, understood as measures or metrics based on specific verifiable data that reduce complexity and summarize and convey key information (Haase et al. 2014), play an important role, especially in spatial ecosystem assessments, in generating concise and comparable results and informing decision makers (Ash et al. 2010, Layke et al. 2012, Kabisch et al. 2016). However, standardized and transferable indicators that are also applicable through open-source data for UGS remain underdeveloped. Indicator approaches for UGS may focus only on vegetation (de la Barrera et al. 2016), exclude contextual aspects and apply only binary ratings of park facilities (Voigt et al. 2014), or focus on broader citywide metrics (TPL 2018). Biernacka et al. (2020) developed a comprehensive set of indicators at the individual UGS level with a focus on barriers (factors limiting UGS use) but utilized mainly specific non-open-source, local data, and presence-only scores for park facilities.

In this interdisciplinary study, we introduce a set of open-data-based, standardized and transferable geospatial indicators relevant for differentiated and systematic assessments of UGS quality in

cities. This will allow for an evaluation of actual quality levels of UGS that are relevant for providing ES, i.e., benefits of nature to citizens as well as ecosystem functioning in the urban context. We chose the city of Leipzig as a central European case to develop our comprehensive set of indicators that incorporates a broad contextual perspective, such as number of residents as well as traffic and related noise and air pollution in the surrounding neighborhoods. We build our indicators on open-access data, assess them in terms of spatial patterns and statistical relationships, and derive a quality score to evaluate individual UGS from a human perspective, i.e., in terms of their relevance to provide recreational ecosystem services (Fischer et al. 2018). We included perspectives from the natural and social sciences in the assessment of UGS, which we understand as urban social-ecological systems relevant to human health and well-being. We identify potential for green space development for our study region and draw conclusions regarding how our indicators can be used in detailed ES assessments and how quality indicators and scores could be adopted and further developed for other case studies as well as by urban planning and management organizations. We transferred our data to an interactive online map application serving as an exploration and decision support tool for users as well as managers of UGS in Leipzig.

DEFINITIONS AND STUDY AREA

Definition of urban green spaces (UGS)

In the context of this study, we evaluated different types of UGS based on a set of criteria describing access and usage restrictions, development potential for the municipality, and the feasibility of spatial assessments (Table 1). Hence, we included all UGS that are city-owned, (more or less) formally planned, and managed open spaces without any restrictions on access or general usage in which a substantial proportion of the area is covered by vegetation (Rupprecht and Byrne 2014, Taylor and Hochuli 2017), i.e., comprising public parks and green squares (parks, hereafter) and excluding all spaces with restricted access (backyards, private gardens/properties, allotment gardens) and spaces with activity restrictions, e.g., cemeteries, where there are no playgrounds and cycling is typically not allowed. We also excluded forested areas in our assessment because of a lack of official demarcation data and the diverse legal frameworks and ownership statuses that result in different management regimes and regulations for public use. Nevertheless, we consider forests, cemeteries, and other excluded UGS to be highly important places for people and nature and integrate them into our approach through the context assessment because alternative green space options potentially reduce pressure (usage intensity) on parks and provide landscape connectivity. In summary, our inclusion criteria and resulting focus on parks are meant to guarantee homogeneity concerning access, usage restrictions, and legal status and thus, ensure comparability among the individual UGS assessed in this study.

Definition of UGS (park) quality: the indicator concept

According to the outlined research needs and questions, we expanded the multidimensional structural diversity approach introduced by Voigt et al. (2014) and defined the quality of UGS and, in our case, parks specifically, as a three-dimensional composite consisting of (semi)natural elements (e.g., vegetation, water bodies, topography), built elements, i.e., infrastructure and

Table 1. Set of criteria (checklist) used to define the focal urban green space (UGS) type for the study. Cases in brackets apply only partially to the respective UGS type, e.g., only minor parts of allotment garden colonies are accessible to anyone (shared areas); leisure (sports) areas are usually owned by the municipality but when leased by sports clubs they are often not accessible for anyone; forests are mainly owned by the federal state rather than by the municipality and are often hard to spatially delimit, i.e., no official demarcation data are available.

| UGS Type | Criteria | | | | | |
|--|-----------------|-------------------|-----------------------------------|---------------------------|--|------------------------|
| | Access any time | Access for anyone | Owned and managed by municipality | No activity restriction † | (Full) development options available for municipality‡ | Spatially delimitable§ |
| Parks and squares | X | X | X | X | X | X |
| Forests | X | X | (X) | X | - | (X) |
| Cemeteries | - | X | X | - | - | X |
| Leisure areas (mainly sports facilities) | - | (X) | (X) | - | - | X |
| Allotment garden colonies | - | (X) | - | - | - | X |
| Brownfields | X | X | (X) | (X) | - | X |
| Back/front yard green | X | - | - | - | - | X |
| Street trees | X | X | X | (X) | - | - |

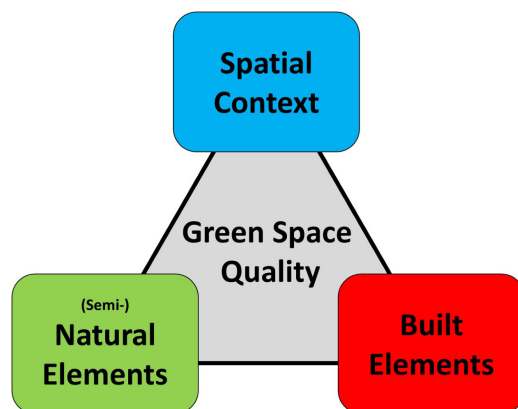
† All outdoor activities allowed (or possible), incl. cycling, sports, dog walking, picnic, etc.

‡ The municipality has all options regarding UGS development, particularly for (re)structuring vegetation, creating playgrounds, sports facilities, dog areas, etc.

§ Demarcation data available/demarcation feasible (e.g., not feasible for the case of street trees: either single trees or, when combined, arbitrary linear structural elements).

facilities (e.g., paths, playgrounds, sanitation), and spatial context within the urban fabric (Fig. 1). The context represents the relationship to or embeddedness within the built, social, and natural environment, e.g., the surrounding infrastructure, the number of residents in walking distance, and the connectivity with other green (and blue) elements. By using the term “semi” natural, we refer to the fact that parks are usually planned and considerably modified by people, i.e., tree and shrub species are selected and planted systematically, and water bodies are usually created artificially, ranging from rather close-to-nature ponds to concrete water basins. Additionally, terrain features such as hills or sinks within our study area are normally manmade. For the purpose of this study, all indicators of park quality had to be available as spatial data, i.e., clearly attributable to a specific park, and quantitatively assessable, i.e., countable or measurable.

Fig. 1. The three-dimensional composite of urban green space quality applied in this study (adapted from Voigt et al. 2014).

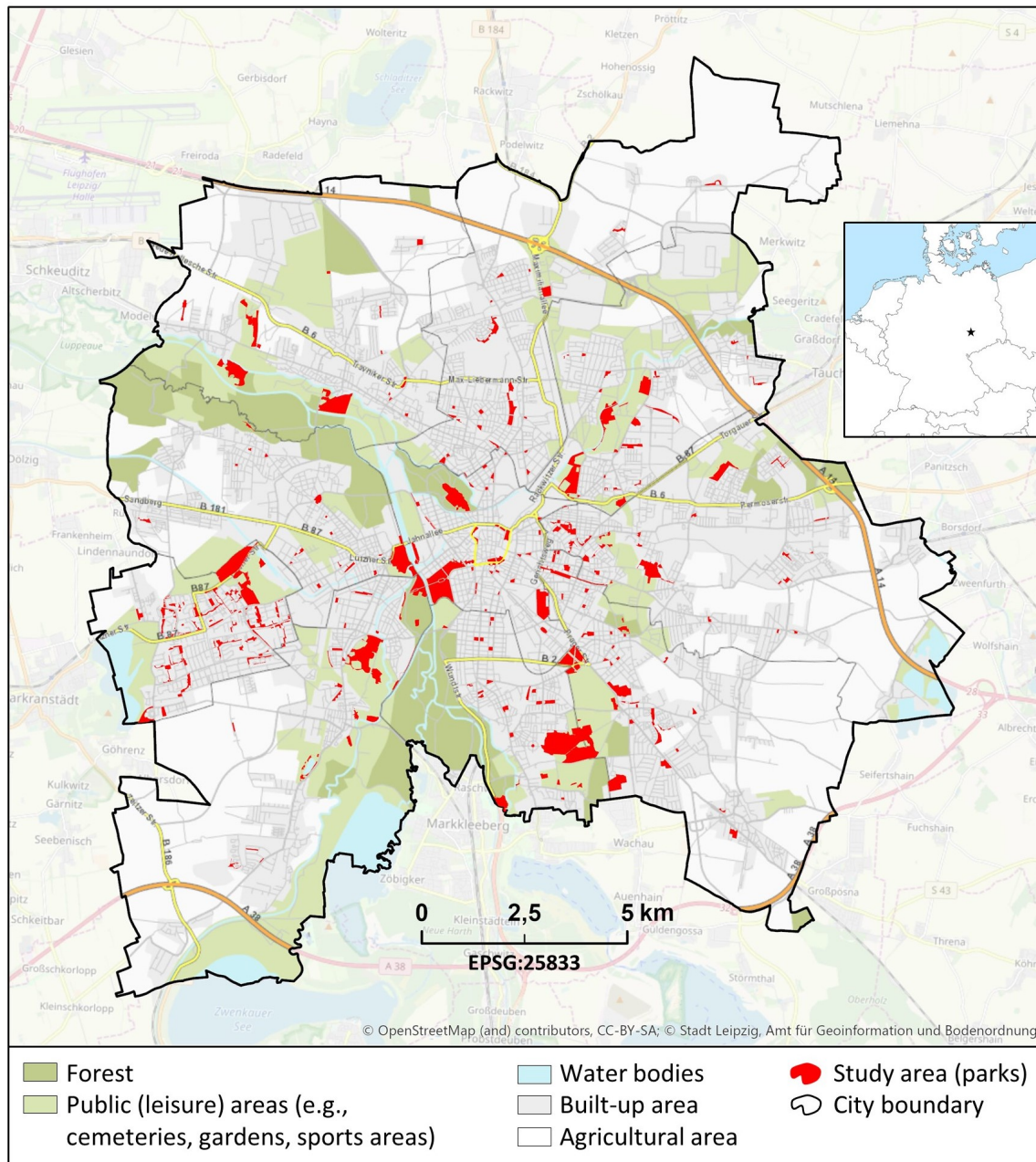


With our definition of park quality and the respective indicators, we tried to combine the human and ecological perspectives. Thus, the indicators are explicitly meant not to be evaluative in a positive or negative way because any element or indicator may be positive for human needs but ecologically negative, such as a high density of sports facilities. Other elements may provide benefits for both ecosystems and human well-being at the same time. Also, trade-offs may appear in terms of ecosystem services, e.g., when a dense stock of trees might be ideal for water regulation or carbon stocks but less beneficial for aesthetic appreciation or certain recreational activities (Rodríguez et al. 2006, Haase et al. 2012). When examining specific needs or problems, e.g., finding parks with the highest potential benefit for park users in terms of recreation (as demonstrated in this study), individual indicators can be selected and transferred into a rating or evaluation system. Regarding ES, our approach focuses on the capacity to provide benefits to people through natural and built elements, and covers aspects of potential demand through the spatial context dimension (Villamagna et al. 2013, Haase et al. 2014). These benefits may arise through physical activities, social interactions, or remaining within a park to relax or enjoy nature and depend on the availability, accessibility, and attractiveness of parks from a human perspective (Beery et al. 2017, Biernacka and Kronenberg 2018, Knight et al. 2018, Hunter et al. 2019). At this point, we understand park quality as the given potential of a park to be used, in contrast to ‘actual use.’ Our approach hence contrasts with others who aim to describe the actually occurring visitation patterns or use of ES and differentiate them by specific needs, e.g., the needs of different age groups, as has been done in studies that use social surveys (Knight et al. 2018, Kabisch and Kraemer 2020).

The case of Leipzig

The assessment of public parks was applied to Leipzig, Germany (Fig. 2). This city faced profound structural changes during the

Fig. 2. Study area, City of Leipzig, with distribution of selected green spaces (parks). Base map credits: OpenStreetMap contributors, CC-BY-SA; Stadt Leipzig, Amt für Geoinformation und Bodenordnung.

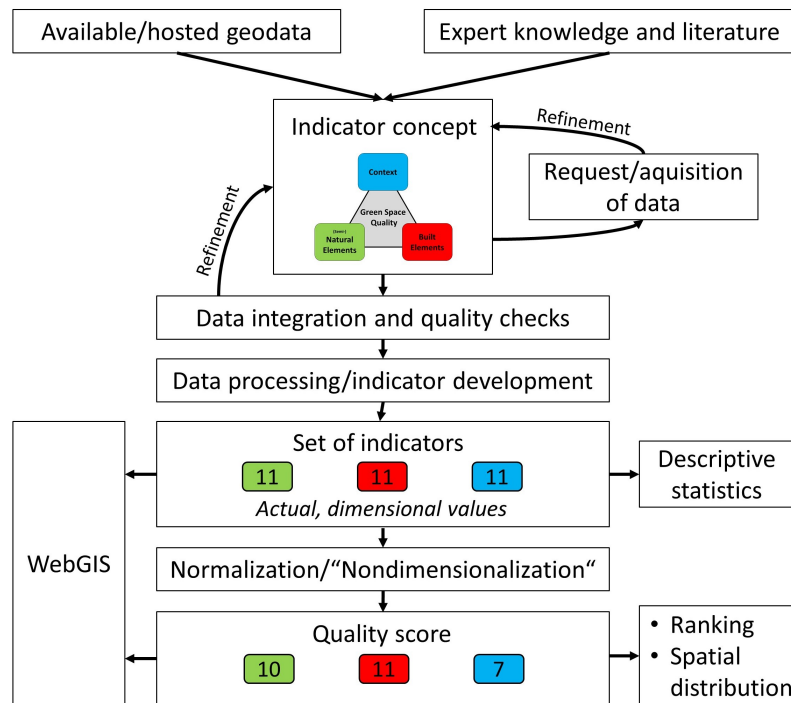


transition period around German reunification, including strong shrinkage and suburbanization processes in the 1990s. Today, Leipzig is one of the fastest growing cities in Germany, with the population projected to rise from approximately 600 to 650 thousand residents by 2030, an increase of more than 8% (Wolff et al. 2016, Heinemann et al. 2019). The rapid increase in population has been linked with increasing traffic, residential development, related environmental impacts, and space allocation issues when trade-offs have to be made between green or gray development (City of Leipzig 2015, 2018a). In addition,

Leipzig is affected by changing climate conditions, notably, a higher frequency of hot summer days ($T_{\max} > 30\text{ }^{\circ}\text{C}$) and drought periods as well as higher frequency and intensity of heavy rainfall events (Bernhofer et al. 2015, Guerreiro et al. 2018).

A substantial proportion of Leipzig is covered by vegetation (45%, 13,415 ha, excluding agricultural areas), of which 36% (4880 ha, 16% of the city) is tree cover (Banzhaf and Kollai 2018). However, only 6% of the total vegetation and 7% of the trees can be found in parks, which cover a total of 889 hectares, or 3% of the city area (City of Leipzig 2018b; Fig. 2). Approximately 67%

Fig. 3. Workflow chart of the study.



of the vegetation in the city (and 45% of the trees) is located in mainly private residential or commercial areas (including allotment gardens), which typically have restricted access. The remaining 27%, or approximately 3700 ha, of green space is composed mainly of cemeteries and the extensive riparian forest greenbelt that crosses the city. These areas are largely available and accessible to the general public and provide over 50% of the tree cover within the municipality. The restoration of former surface mining areas created the many lakes that closely surround the city (largely outside the municipal area) and serve as important recreational areas for residents and tourists. In this study, we focused on parks (red areas in Fig. 2) but accounted for the remaining green areas (green shades in Fig. 2) through the context assessment.

DATA AND METHODS

Data sources

For the delineation of parks, we acquired official outline data (cadastral data) from the city administration that contain all publicly managed green spaces in the city (3390 total spatial entities), including roadside greenery (City of Leipzig 2018c). To obtain a meaningful representation of parks, we ran extensive preprocessing and cross-checking of the cadastral data (for details on the data source and processing, refer to Appendix 1) and defined a minimum size of a quarter hectare (0.25 ha, e.g., 50 x 50 m) based on sensitivity analysis. This size proved to be the best threshold for excluding the vast amounts of roadside green strips and ensuring minimum functionality, i.e., the possibility of staying in the area for a certain purpose. At the same time, this threshold does not exclude commonly used places such as pocket

parks, which would have been overlooked at higher thresholds of, e.g., 0.5 ha. This resulted in a dataset of a total of 249 parks that constituted our overall study area.

To develop the park quality indicators, we used various data types and sources, preferably available as open-source data, to ensure the reproducibility and transferability of the study (cf. Table 2). Data acquisition was an iterative process driven by the three-dimensional indicator concept and by data availability, suitability, and quality (cf. Fig. 3, refinement loops). A dataset was determined to be suitable if (1) it provided information regarding park quality in any aspect, i.e., biophysical, built, or socio-cultural characteristics; (2) it was available for the entire city, i.e., all parks (spatial explicitness); (3) it was detailed enough to allow for differentiated park-specific assessments, e.g., vital statistics at the district level covering more than one park would have been too coarse (spatial resolution); and (4) it was not outdated compared to our reference year of 2018 (all data were within a 10-year time frame). We evaluated the quality of the datasets with the criteria of thematic reliability as well as spatial accuracy and completeness (details cf. Appendix 1, Table A1.1).

For the assessment of the vegetation structure within and around the parks, we used freely available very-high-resolution and evaluated (ground-truthed) land-cover data for 2012 (Banzhaf and Kollai 2018). We extracted data on the built elements and infrastructure from OpenStreetMap (OSM, hereafter; OpenStreetMap contributors 2019) using the QuickOSM plugin in QGIS software (v. 3.6.0, QGIS Development Team 2019). Additional land-cover and land-use data were acquired from the Federal Agency for Cartography and Geodesy (GeoSN 2018a). A digital elevation and surface model and data for the protected areas were freely

Table 2. List of indicators per park quality dimension and their characteristics. Cross marks in brackets indicate minor relevance for the respective ecosystem service or data that are only partially open. Acronyms used: R/M = regulation and maintenance, C = cultural, P = provisioning, QS = quality score, OD = open data, SD = standard deviation.

| Indicator | Acronym | Unit | Description/method [†] | Relevance | | | | | Source | OD |
|--|-----------|------------------------|---|--|--------------------|-----|-----|----|--------------------------------------|-----|
| | | | | General (narrative) | Ecosystem Services | | | QS | | |
| | | | | | R/M | C | P | | | |
| Natural elements | | | | | | | | | | |
| Area | Area | ha | Total area of park (size) | General capacity (visitors, habitat) | X | X | (X) | X | City of Leipzig 2018c | - |
| Shape index (SI) | Shape | - | Deviation from circle shape (SI = 1) | Geometry effects (compactness, core area) | X | X | - | X | City of Leipzig 2018c | - |
| Terrain index | Terrain | - | Mean value between normalized SDs for slope and elevation | Terrain variability (aesthetics) and slopes for sports | X | X | - | X | GeoSN 2018b | X |
| Total vegetation cover | VegTotal | % | Proportion covered by vegetation | Ecology, greenness as aesthetic factor, climate regulation | X | X | - | X | Banzhaf and Kollai 2018 | X |
| Vegetation balance | VegBal | - | Balance among vegetation types (trees, shrubs, grass) | Vegetation composition (ecology, aesthetics) | X | X | (X) | X | Banzhaf and Kollai 2018 | X |
| Mean tree height | TreeH | m | Mean height of tree coverage | Proxy for park age/persistence, shading potential | X | X | (X) | X | Banzhaf and Kollai 2018, GeoSN 2018b | X |
| Shape index of vegetation | VegConf | - | SI of combined tree and shrub coverage | Vegetation configuration (spatial variability) | X | X | - | X | Banzhaf and Kollai 2018 | X |
| Water cover | Water | % | Proportion of water bodies (on the ground) | Aesthetics, ecology, climate | X | X | - | X | GeoSN 2018a | X |
| Stream density | Stream | m/ha | Stream/ditch length per ha | Habitat, ecology | X | (X) | - | - | GeoSN 2018a | X |
| Tree diversity | TreeDiv | No./ha | Number of tree species per ha | Aesthetics, ecology | X | X | - | X | City of Leipzig 2018c | (X) |
| Edible plants | Edible | No./ha | Number of sites of edible plants per ha | Food provision, place attachment | - | X | X | X | Terra Concordia 2019 | X |
| Built elements | | | | | | | | | | |
| Path density | Path | m/ha | Length of tracks/paths per ha | Walking, cycling, etc. | (X) | X | - | X | OpenStreetMap (OSM) | X |
| Playground density | Play | No./ha | Number of playgrounds per ha | Children's play | (X) | X | - | X | City of Leipzig 2018c and OSM | (X) |
| Sports facilities density | Sport | No./ha | Number of sports facilities per ha | Sports activities | (X) | X | - | X | City of Leipzig 2018c and OSM | (X) |
| Sitting facilities density | Sit | No./ha | Number of benches per ha | Resting, social interaction | - | X | - | X | OSM | X |
| Cultural and historic elements density | Cultural | No./ha | Sculptures, monuments, memorials, archaeol. sites, fountains, per ha | Aesthetics, historical/cultural identity | - | X | - | X | OSM | X |
| Ornamental plants/flower beds | Orna | % | Proportion of flower beds | Aesthetics | (X) | X | - | X | OSM | X |
| Dog parks | Dog | % | Proportion of dog park area | (legal) free run for/with dogs | (X) | X | - | X | City of Leipzig 2018c | (X) |
| Waste bin density | Waste | No./ha | Waste bins per ha | Cleanness, aesthetics | (X) | X | - | X | OSM | X |
| Toilets density | WC | No./ha | Number of public toilets (incl. 50m surrounding) per ha | Promoting usability, cleanness | (X) | X | - | X | OSM | X |
| Bicycle parking density | Bike | No./ha | Number of bike rack sites (incl. 10m surrounding) per ha | Promoting usability and safety | - | X | - | X | OSM | X |
| Food/drink service density | Food | No./ha | Number of food/drinks services (incl. 50m surrounding) per ha | Promoting park usage | - | X | - | X | OSM | X |
| Context | | | | | | | | | | |
| Distance to public transport | PubTrans | m | Distance to next public transport station | Accessibility | - | X | (X) | X | OSM | X |
| Noise | Noise | dB | Mean value of max. noise values for cars, tram or railway | Noise exposure | (X) | X | - | X | BKG 2018, City of Leipzig 2018c | (X) |
| Near water | WaterNear | % | Water area within 100 m buffer | Aesthetics, leisure, ecology | X | X | - | X | GeoSN 2018a | X |
| Standard ground value | SGV | €/m ² | Mean standard ground value for residential area within 500-m buffer | Equity | - | X | (X) | X | City of Leipzig 2018c | - |
| Traffic/emission exposure | Pollution | g/m ³ *a*ha | NOx and PM2.5 emissions within 50-m buffer per ha | Pollution exposure, safety (traffic) | (X) | X | - | X | City of Leipzig 2018c | - |
| Surrounding population | Pop | No./ha | Number of residents within 500-m buffer per ha park area | Demand by residents | - | X | (X) | X | City of Leipzig 2018c | (X) |
| Surrounding commercial area | PopDay | % | Area for commercial use and public amenities in 500-m buffer | Proxy for demand by day/working population | - | X | (X) | X | GeoSN 2018a | X |
| Usage intensity | Intensity | No./ha | Pop indicator weighted by available UGS alternatives in 500 m buffer | Proxy for usage pressure, crowding, ecology | (X) | X | - | ‡ | City of Leipzig 2018c, GeoSN 2018a | (X) |
| Surrounding shrubs and trees | VegNear | % | Proportion of trees and shrubs within 500 m buffer | Landscape connectivity on smaller scale | X | (X) | (X) | - | Banzhaf and Kollai 2018 | X |
| Urbanity index | Urbanity | -(m) | Distance to edge of built-up area weighted by distance to city center | Landscape connectivity on larger scale/ with rural area | X | (X) | - | - | GeoSN 2018a | X |
| Protected area index | PAI | % | Weighted (by IUCN cat.) proportion of protected area | Ecological valuation, ecology | X | (X) | - | - | LfULG 2018 | X |

[†]For details on workflow, i.e., how each indicator was derived from the data, please refer to Appendix 1, Table A1.2.

[‡]Indicator has been excluded from quality score because of high collinearity.

available from the Federal State of Saxony (GeoSN 2018b, LfULG 2018). The city administration of Leipzig provided us with several socioeconomic datasets and spatial datasets for tree

species, playgrounds, and emissions of air pollutants and noise from traffic (City of Leipzig 2018c). We complemented the noise data with information on railway-related emissions from the

Federal Railway Authority (BKG 2018). Finally, data were acquired from a nationwide (online) platform that collects spatial information on edible plants (mainly fruit trees and shrubs) available in publicly accessible areas (Terra Concordia 2019). We used EPSG:25833/UTM zone 33N as the spatial reference system and reprojected data whenever necessary. For further details on the data sources, including their spatial scales and time references, please refer to Appendix 1, Table A1.1.

Development of park quality indicators

Following our three-dimensional park quality concept and the acquired data, we developed a set of indicators for natural elements, built elements, and context to assess the quality of 249 parks in the City of Leipzig (Fig. 3; Table 2). Each indicator is based on existing evidence from previous studies (e.g., Voigt et al. 2014, Massoni et al. 2018, Hunter et al. 2019, Kabisch and Kraemer 2020, Vierikko et al. 2020) identifying these park quality criteria as having particular relevance to ES provision (cf. relevance column in Table 2). For instance, Weber et al. (2014) and Zhou et al. (2011) found a significant influence of the size, shape, and configuration of UGS on land surface temperature (climate regulation service). Vegetation structure, particularly the composition (balance) and configuration (spatial distribution) of trees, shrubs, and grass, has effects on air quality, (micro)climate, leisure activities, and faunal biodiversity (Lehmann et al. 2014, Voigt et al. 2014, Brunbjerg et al. 2018, Mexia et al. 2018, Xing and Brimblecombe 2019). Plant species diversity not only matters for ecosystem functioning but also directly influences the human perception of nature and well-being (Carrus et al. 2015, Palliwoda et al. 2017, Cariñanos et al. 2019). Blue infrastructure, including that around parks, is equally important as habitat and for visitors and plays a central role in water and climate regulation (Derksen et al. 2015, Gunawardena et al. 2017). Infrastructural elements and facilities, which together form the built-elements dimension, are key to attracting park visitors and stimulating physical activities (Giles-Corti et al. 2005, Voigt et al. 2014, Kabisch and Kraemer 2020). We developed the indicators for built elements by mapping the built-element frequency in terms of the number of facilities. This approach is in contrast with the simple presence-absence scores that have been applied in most previous studies (Taylor et al. 2011, Voigt et al. 2014, Massoni et al. 2018, Biernacka et al. 2020). We assessed the accessibility and availability of parks through the surrounding (day and night) population and the distance of the parks to public transport. As contextual factors that somewhat impair park quality (Arnberger 2012, Rey Gozalo et al. 2018, Kumar et al. 2019), we set up indicators for noise, air pollution, and usage intensity (potential crowding). We incorporated a broader ecological context by developing indicators for the surrounding vegetation, urbanity, and protection level, which might also be relevant for attracting visitors.

To ensure a meaningful and comparable assessment across parks of variable sizes, we set up all indicators as density or fractional values relative to the park area. However, we kept “area” itself as a key indicator of park capacity, which is relevant from both the human and ecological perspective. Through the high-resolution data available for this study, we specifically advanced the spatial depth of existing UGS assessments. All indicators were processed with ArcGIS Pro software (Esri Inc.). For details on the workflow for each indicator, please refer to Appendix 1, Table A1.2.

Statistical assessment of park quality indicators

We assessed the statistical distribution of the park quality indicators using descriptive statistics (cf. Fig. 3). To determine how independent and complementary our indicators were, we first tested for collinearity by applying the Pearson correlation coefficient in a correlation matrix using the *corrplot* package (Wei and Simko 2017) in R, version 3.6.2 (R Core Team 2019). Furthermore, we assessed each indicator separately for its value distribution across all 249 observations (parks) and applied a combination of violin and box plots in R using the packages *ggplot2* and *tidyr* to provide a visual representation (Wickham 2016, Wickham and Henry 2020). We also tested for the possible clustering of data through a principal component analysis (PCA) as well as k-means and hierarchical clustering analysis using the *stats* and *factoextra* packages (Kassambara and Mundt 2019, R Core Team 2019).

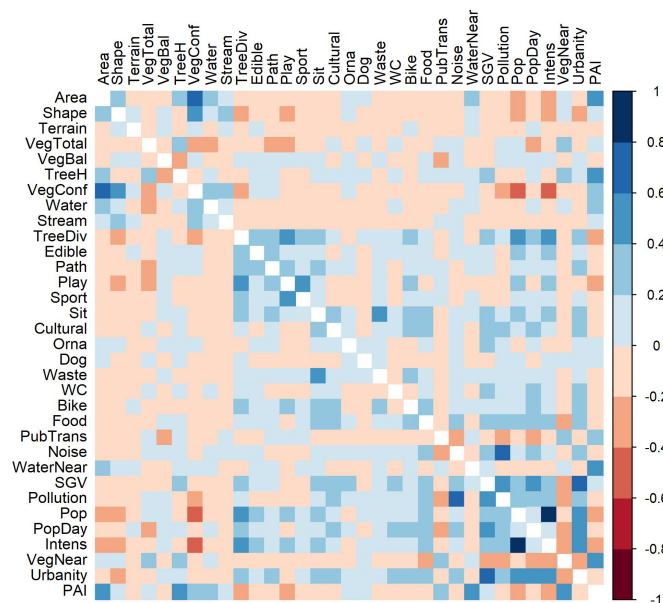
Quality score and spatial distribution

To provide a tangible and practice-oriented evaluation of parks that is particularly suitable for city planners and dwellers, we transformed a set of indicators with relevance to the provision of recreational ecosystem services (Fischer et al. 2018) into scores (Table 2 for relevance to cultural ES). Therefore, we selected 28 (out of 33) indicators and normalized them to a range from 0 to 1 to obtain harmonized, nondimensional values across indicators (Fig. 3; Table 2). We excluded a total of four indicators that were important from an ecological standpoint but less in their relevance for recreational ES within the parks (Urbanity, VegNear) and/or that applied to only a minor subset of the 249 parks (PAI for 37, Stream for 13 cases). Additionally, we excluded the usage intensity indicator (Intensity) because of its high correlation with the population indicator (Pop; Fig. 4). In total, there remained 10 indicators for natural elements, 11 for built elements, and 7 for the context dimension (Fig. 3). To derive the final scores for each dimension, we summed all selected and normalized indicators within each dimension. At this point, we inverted the values of indicators (1 - the normalized value) known to have rather adverse relations with park quality (i.e., increasing indicator values led to decreasing park quality, e.g., noise or distance to public transport). We did not apply any weighting to the indicators because our study presents a methodological (theoretical) framework that is not parameterized through locally specific data or expert-based judgment. For spatial representation, we transferred the three scores into an RGB-color composite, i.e., a raster file composed of three layers/bands (with the built-elements score in red, the natural-elements score in green, and the context score in blue; cf. also the online GIS presentation of this study at <https://arcgis.is/0GXafX>). To obtain an equal value range for each color space, we normalized the score values to a range from 0 to 1.

We created a total quality score for each park by summing up the normalized dimension scores (as per the RGB composite) and weighted the sum by the standard deviation between these scores to account for the balance between dimensions. We then developed a map depicting the spatial distribution of parks and their quality scores, thus revealing gaps in park provision in terms of spatial coverage as well as quality, particularly in residential areas. For this, we first created 500-m buffer zones around the parks (with their respective quality scores) to account for the effect of catchment areas, i.e., the availability of the park to the

neighborhood. As spatial reference units, we then constructed a layer of regular hexagons of 0.25 square kilometers covering the entire city instead of using irregular and arbitrary administrative units. Finally, we calculated a quality score for each hexagon by averaging the underlying quality scores of parks and their 500-m buffers (the spatially weighted means). When a hexagon covered only one park (incl. the buffer), it was assigned the quality score for that single park. In addition to avoiding the use of administrative units, this hexagonal representation has visual and analytical advantages over rectangular grids (rasters), e.g., it does not create horizontal or vertical lines, and each unit is surrounded by equidistant hexagonal neighbors (Birch et al. 2007).

Fig. 4. Correlation matrix for the 33 park-quality indicators with red shades for negative and blue shades for positive Pearson coefficients.



RESULTS

Park quality indicators for the city of Leipzig

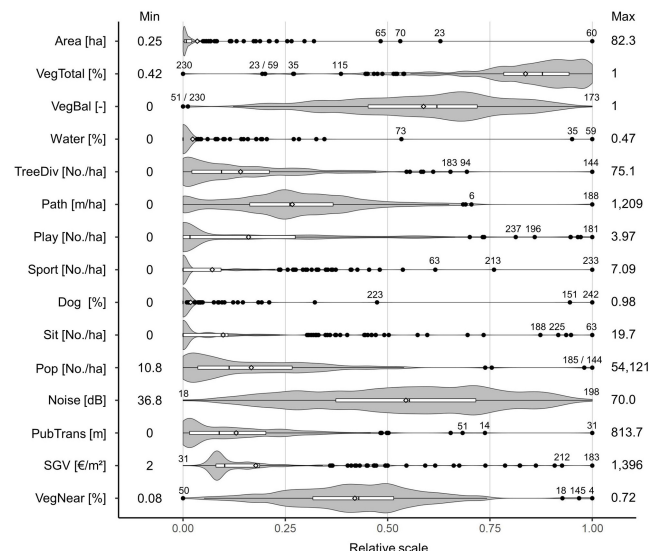
Our sequential concept with iterative data acquisition, integration, and processing (Fig. 3) resulted in a total set of 33 indicators that were evenly distributed across the dimensions of natural elements, built elements, and context (11 indicators per dimension; Fig. 3; Table 2). Nearly all indicators were particularly relevant for the provision of cultural ES and were thus linked to recreation, physical activity, and well-being. Four indicators rather focused on ecological functions (cf. Table 2). We were able to use exclusively open-source data for 22 indicators, and another 9 indicators were based partially on freely available data (for details cf. Appendix 1, Table A1.1).

The Pearson's correlation coefficients between each pair of indicators showed that indicators were fairly independent from each other (Fig. 4). Low or even no significant correlation indicated complementarity in determining park quality. Only 4 (out of 528) indicator pairs had a positive, significant Pearson coefficient of at

least 0.6, and none of the pairs had a negative correlation coefficient below -0.6. The highest positive correlation coefficient, 0.99, was between population (Pop) and usage intensity (Intensity) because population is a direct input for the intensity indicator. Highly positive correlations, all between 0.6 and 0.7, were found between the area of parks (Area) and the vegetation configuration (VegConf), between the emissions of air pollutants (Pollution) and noise, and between urbanity (Urbanity) and the standard ground value (SGV). Because of the overall high degree of independence among indicators, we did not achieve meaningful results from the PCA or cluster analyses.

The distribution of values varied strongly across indicators and the 249 parks assessed (Fig. 5, for full list of parks and their respective indicators; cf. Appendix 2 or the web map application at <https://arcg.is/0GXafX>). Over half of the analyzed parks were below 1 ha in size (median = 0.9), and only 16 were larger than 10 ha. However, we found an overall high total vegetation cover with a median of 93% and a minimum of 43% and an averagely good balance of vegetation types among grass, shrub, and tree cover (VegBal, median = 0.62). Only one green space had no tree cover at all (park ID 230), and one was nearly completely covered by trees (98%, ID 51). The standardized tree diversity value revealed that approximately 100 parks host at least 10 tree species per ha; the park with the highest score was a small playground area with 20 species on only 0.27 ha (ID 144). In 27 cases, we detected ponds or lakes, which in 2 cases accounted for nearly half of the total park area.

Fig. 5. Violin plots for selected indicators (5 per dimension) with boxplots (white bars, median as vertical black line, whiskers as horizontal black lines), and mean value indicators (diamonds). Relative scale 0-1 (y-axis) applies for specific value ranges marked by the respective minimum and maximum values. Numbers above the plots represent IDs of selected parks with particularly high or low values. Note: violin plots illustrate the density of observations using a Gaussian kernel density estimator.



In the dimension of built elements, we found an average path length per ha of approximately 320 m, with the highest value of approximately 700 m in a 0.6-ha-sized park with a high vegetation cover of 82%. For 22 parks, mostly strips along roads, our data showed no paths at all. Overall, parks were better equipped with playgrounds than with sports areas or facilities. Although 132 parks had at least 1 playground (maximum 3 per park, maximum 4 per ha), only 92 parks offered any sports facilities. However, the number and density of sports facilities reached up to 6 per green space (ID 152), or 7.1 per ha (ID 233). We mapped official off-leash dog run areas in only 28 parks, 2 of which were completely dedicated to dog activities. Sitting facilities such as benches, based on OSM data, were found in nearly half of the assessed parks, constituting a mean value of 1.9 facilities per ha. However, only 32 cases provided at least 5 sitting options per ha.

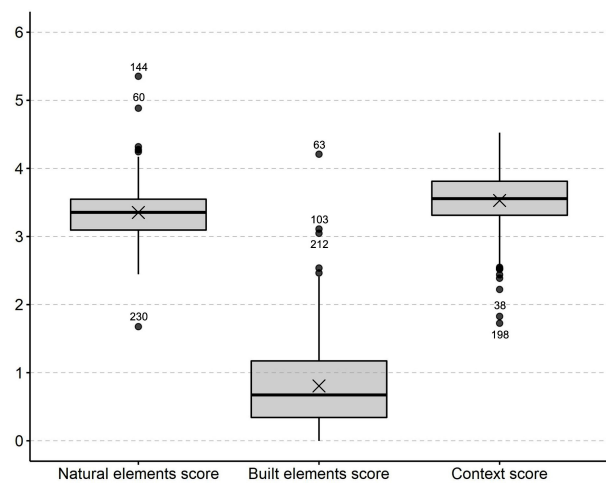
In terms of context indicators, the results showed that on average, approximately 9000 residents are supplied by 1 ha of parks (excluding other public green space types such as forests or cemeteries) in their closely surrounding neighborhood area (mean of the Pop indicator). This potential pressure (overuse or crowding) was mitigated by approximately 20% through public green space alternatives around individual parks, including cemeteries, forests, or other parks (Intensity indicator, mean = 7174). Two parks faced a particularly high demand, with over 50,000 residents per ha living in a 500-m buffer zone (IDs 144, 185, Fig. 5), and 6 cases were considered rather secluded, with fewer than 100 neighboring residents per ha. In addition, 47 parks were likely to be additionally used by working people, with at least one-third of the surrounding 500 m buffer zone being devoted fully or partially to work activities (commercial use or public amenities; cf. PopDay indicator in Table 2). We found that 148 or 59% of parks had a maximum distance to public transport stations of 100 m (median at 72 m). However, 4 of our parks were further than 500 m (linear distance) away from any public transport (IDs 14, 31, 33, 51), and 3 of these were among the 6 cases with fewer than 100 neighboring residents per ha. The total average of the maximum noise levels was 55 dB when each of the park-specific values was averaged over the respective green space area. The value of 65 dB, which is commonly reported as the health-relevant threshold (WHO 2018), was found to be exceeded in 23 parks, and 5 parks were particularly calm, with an average maximum noise level below 40 dB (IDs 18, 33, 101, 176, 245). Mean standard ground values (SGV indicator), i.e., reference prices for undeveloped land, for the areas surrounding parks showed a wide range, from 2 up to nearly 1400 €/m². Although 50% of parks were below a mean SGV of 144 €/m², we found 8 cases to be above 1000 €/m² (e.g., IDs 183, 212). The latter were located in or around the city center, which is in accordance with the high positive correlation of the mean SGV with the urbanity index (Fig. 4). The mainly ecological indicator of surrounding shrubs and trees (VegNear) showed that, on average, one-third of the vicinity of parks in Leipzig are covered by trees or shrubs. The top three parks in this category (IDs 4, 18, 145), which had at least two-thirds tree/shrub cover in the neighboring area, are largely surrounded by forests. One case with less than 10% surrounding trees or shrubs (ID 50) was located in a rural environment surrounded by croplands.

Quality score and spatial patterns of park quality

Our scoring approach for evaluating park quality in terms of recreational ES resulted largely in normally distributed natural-elements and context scores (symmetrical around the median/mean), whereas the built-elements score was rather skewed, with distant upper outliers (Fig. 6). Notably, the built-elements score reached relatively low values, despite containing the highest number of indicators. This reflects that the majority of parks reach low scores, with many indicators in the built-elements dimension showing frequent zero values (cf. Fig. 5). Overall, 13 parks did not score at all in terms of built elements. Note that the achievable maximum for each dimension score is defined by the number of indicators in each dimension (cf. Fig. 3), i.e., 10, 11, and 7 for natural elements, built elements, and context, respectively.

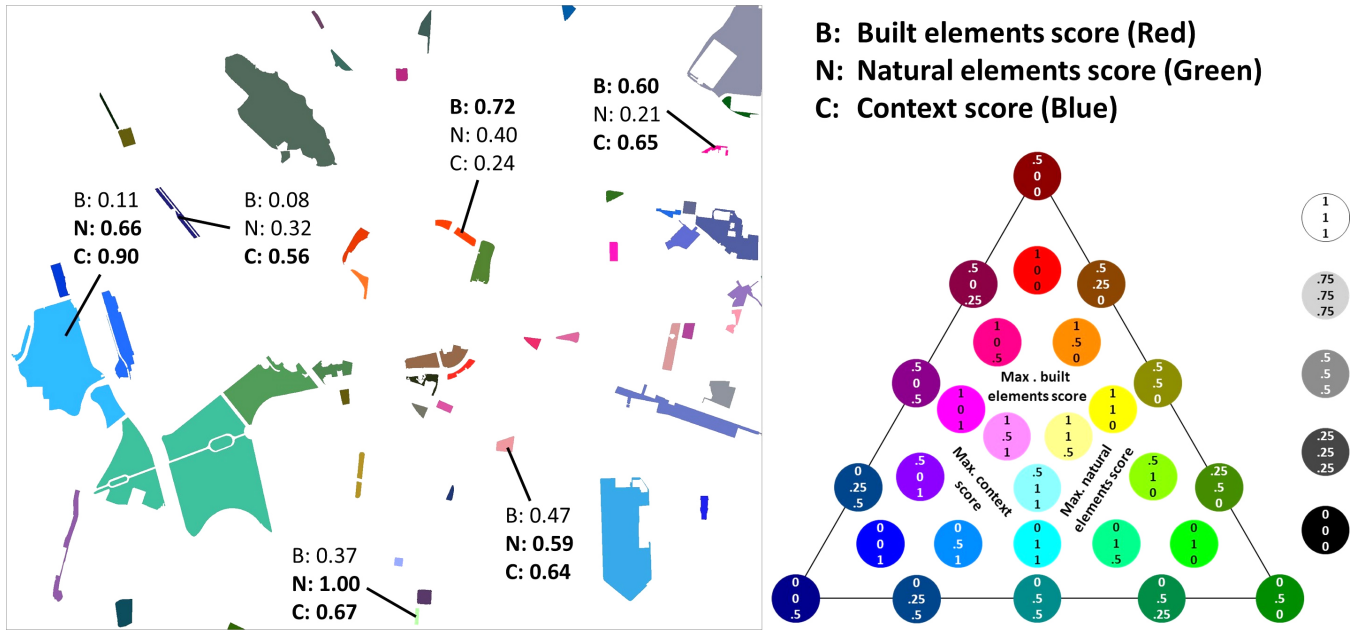
Figure 7 shows a detailed view of the central part of Leipzig depicting parks with their individual RGB-color composite values based on their normalized scores per park quality dimension. This representation aims to intuitively display the park-specific interrelations of the dimension scores and thus to identify the dominant dimensions. Notably, most smaller parks surrounding the city center were dominated by high built-elements scores (red shades), whereas larger parks in the west and south were characterized by dominant context and/or natural-elements scores (blue and green shades). The top-scoring park in the natural-elements dimension is visible in light green at the southern edge. This park is the same playground area that had the highest tree species density (ID 144).

Fig. 6. Boxplots for park quality dimension scores based on summed up values of single indicators (each normalized to a range from 0 to 1). Mean value marked with a cross. Numbers above or below dots represent the park IDs of outliers.



The total quality scores for the parks were dominated by smaller parks. The top 30 parks by quality score (12% of our sample) had a range of park sizes from 0.25 to 2.27 ha, with only 5 parks above 1 ha. We investigated the two highest- and lowest-scoring parks to present more details about individual park characteristics (Fig. 8; for the full list cf. Appendix 2 or the web map application at <https://arccg.is/0GXafX>, incl. imagery as base maps). Both top

Fig. 7. Detail of the inner City of Leipzig depicting parks with specific RGB-color composite derived from normalized scores per park quality dimension. Mode of visualization: normalized dimension scores (0 to 1) are transformed to a color space (0-255), with red representing built-elements score, green representing natural-elements score, and blue representing context score. Light shades indicate high, dark colors low index values, e.g., as 0-0-0 would be black (0-0-0 RGB-color mix) and 1-1-1 would be white (255-255-255 RGB-color mix). For full and interactive view of the data, please refer to the online GIS under <https://arcg.is/0GXafX> or download all results as geodata from Kraemer and Kabisch 2021.



scorers (IDs 63, 191) had above-average tree species diversity and built elements, and both parks are available to at least 10,000 residents living in a 500-m vicinity. In particular, park 63 has one of the highest sports facilities densities of all 249 assessed cases (cf. Fig. 5) and a considerable amount of surrounding water (13% water cover within 100-m buffer). Park 191 is particularly well provided with food or drink services and very accessible via public transport. On the other hand, the two lowest ranked parks are characterized by high levels of noise and air pollution, little equipment with built elements, and notably high mean standard ground values in the neighborhood. Park 38 faces particular usage constraints because of its unfavorably shaped area (a width of only approximately 15 m) that is mainly covered by trees.

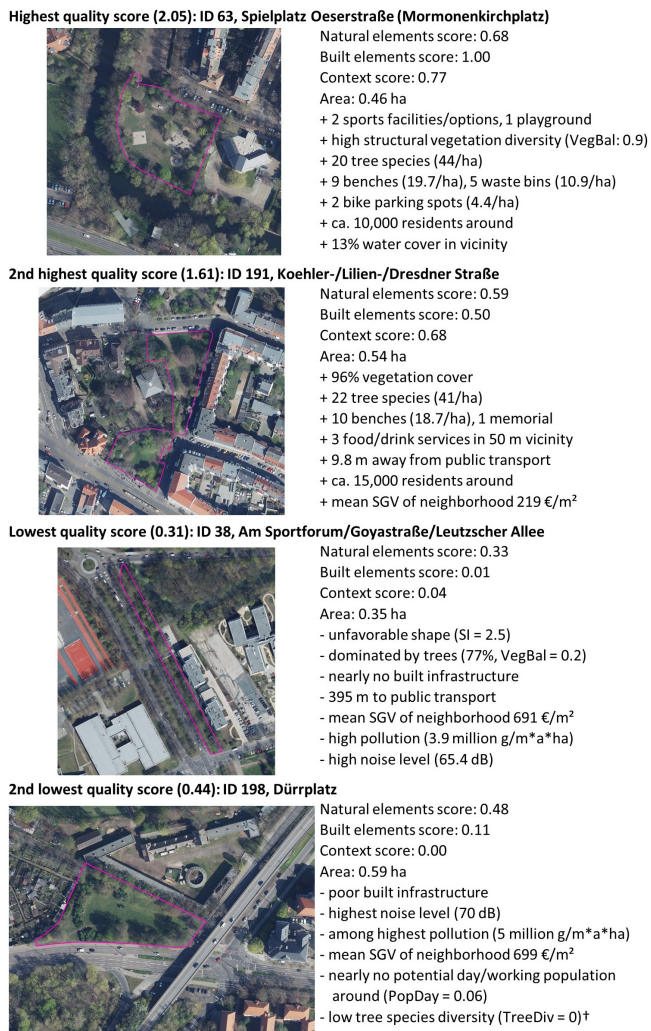
The spatial distribution of the parks and their individual quality scores reveal an uneven supply of green space quality (Fig. 9). We found particularly high quality scores along a belt in the western part of Leipzig (darker/brown shades), ranging from the city's major districts Alt-West to Südwest (for a detailed map incl. the local districts, please refer to the web map application at <https://arcg.is/0GXafX>). There are also smaller spots of notably high green space quality in the eastern and northern parts of the city (the major districts of Nord, Ost, and Südost). The lowest quality scores are prevalent toward the outskirts of Leipzig (brighter/yellow shades). These suburban areas are characterized by agricultural surroundings with only a few, mostly small parks that are poorly equipped with built elements. Despite our extensive approach to delineating the spatial coverage of the quality scores (using 0.25-km² hexagons intersecting 500-m buffer zones around parks), we identified some residential areas (dark gray in Fig. 9)

that do not have any publicly managed and accessible green space at all within a distance of 500 m (e.g., the Alt-West and Südost districts). However, many gaps, especially at the outskirts, have potential compensatory green spaces, such as nearby forests or extensive agricultural areas located inside or outside the administrative city area.

DISCUSSION

Urban green spaces have gained attention because of their increasing relevance for dealing with urbanization, aging, the biodiversity crisis, and climate change (Elmqvist et al. 2018, McDonald et al. 2018). Our study presents a detailed, systematic, citywide, quality assessment of publicly available and managed UGS (parks) in Leipzig, Germany. We hereby deliver a comprehensive methodological framework for future UGS evaluations. Based on ready-to-use open and administrative data, we developed a novel set of 33 extensive indicators covering infrastructural, environmental, and socio-demographic aspects that are relevant to the quality of parks from a human perspective, i.e., for providing ecosystem services (ES) as well as for ecological processes. The indicators were organized into three dimensions: natural elements, built elements (infrastructure), and spatial context. Testing for collinearity through Pearson's correlation showed that the indicators are highly independent and thus can be applied complementarily in UGS assessments. We demonstrated how to use our indicators to evaluate the quality of parks through a multilevel scoring approach. Furthermore, we conducted a spatial gap analysis to identify potential areas in which planning efforts could begin to improve the current UGS supply situation.

Fig. 8. Details for the parks (purple outline) with the two highest and lowest quality scores. Special positive features are marked with plus signs (+), negative features with minus signs (-). The size of each park has no particular negative or positive effect in the respective calculations. Note: SGV = standard ground value. †Note: this is due to incomplete tree cadaster dataset; actual tree cover of 44%. Source of background imagery: City of Leipzig, Amt für Geoinformation und Bodenordnung.

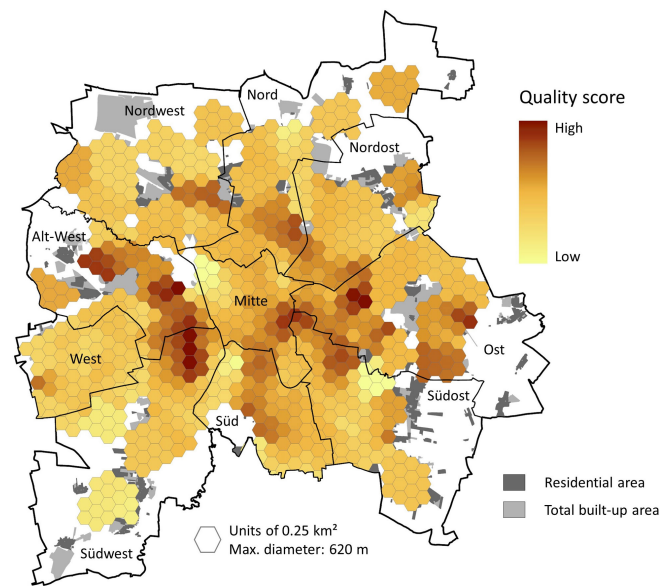


Strengths

Our study advances previous research on UGS by integrating official and other public open data on UGS structure and incorporating the spatial context dimension in a comprehensive way. By including indicators such as the number of residents living near parks or impairment because of traffic noise, we shift the analysis of individual green spaces closer to the actual systemic properties of the urban fabric, e.g., potential demand in neighborhoods, accessibility, and ecological functionality. Voigt et al. (2014) and Massoni et al. (2018) argued that accessibility and tranquility are important factors determining green space

use. However, although Massoni et al. (2018) included only access to public transport in their analysis, Voigt et al. (2014) did not include any contextual factors. Other studies, such as Taylor et al. (2011) and Vierikko et al. (2020), did include context measures but had to narrow down their UGS samples because of methodological restrictions. The recent study by Biernacka et al. (2020) focused on context regarding planning and accessibility by assessing access restrictions but did not consider potential green space demand from nearby residents or ecological factors, such as connectivity with nearby green areas or the city's surrounding areas. In this study, we provide methodological approaches to fill these research gaps.

Fig. 9. Spatial distribution of the park quality score in the City of Leipzig depicted by hexagonal units of 0.25 square kilometers. Gray shades represent built-up and residential areas in empty hexagons, i.e., that neither contain parks nor intersect the 500-m-buffer zone of any park. For better orientation, the map is overlaid by Leipzig's major districts. For an interactive view of the map, please refer to the online GIS at <https://arcgis/0GXafX> or download geodata from Kraemer and Kabisch 2021. Source of background and district data: City of Leipzig 2018c, GeoSN 2018a.



The combination of various high-resolution and spatially explicit data allowed us to run a citywide and fine-scale analysis that overcomes the common trade-off in UGS research of being either broad-scale and covering a larger area or mapping detailed green space structure in only selected instances of green space (Voigt et al. 2014, Smith et al. 2017, Dennis et al. 2018). Such a broadened perspective may be important to improve the understanding of linkages or barriers between residents and urban green areas, how and to what extent ES are generated, and which health effects are attributable to park visits (Kremer et al. 2016, Dickinson and Hobbs 2017, Ekkel and de Vries 2017, Markeyvych et al. 2017). Moreover, as we used mainly open-access (input) data, our study allows for feasible adaptation, extension, and further improvement. The transferability of our approach to other cities

is particularly facilitated by the use of globally available OSM data, which might be complemented by more specific data at the city level. Although most of our indicators are based on common and straightforward approaches, we also developed novel and more complex indicators (e.g., urbanity and terrain index) that might be applicable in other fields of research, such as detailed ES assessments (e.g., of climate regulation or recreational services) or models such as Urban InVEST (cf. van Oudenhoven et al. 2018 for criteria on transferability, data availability, and relevance of indicators). Our complex set of indicators, covering many aspects apart from vegetation structure, may be also suitable for seasonally differentiated ES assessments, hence accounting for the timing of nature and related ES (Willemsen 2020).

Our innovative approach differentiates structural elements by both quality and quantity, i.e., incorporating not only presence but also the quantity of certain elements. The normalization of quantity measures (by area) allowed us to compare UGS irrespective of their sizes. Other studies have only partly considered quantity of structural elements in their application of structural diversity mapping, and some highlighted this as a potential limitation (Giles-Corti et al. 2005, Taylor et al. 2011, Voigt et al. 2014, Massoni et al. 2018, Biernacka et al. 2020, Vierikko et al. 2020). The quantity dimension, i.e., how much or how many elements are provided (e.g., number of playgrounds or benches), coupled with the potential demands of local residents is important when assessing the actual attraction and usage capacity of UGS. For example, having one small playground in a park with a high population number in the neighborhood may lead to overuse and, thus, to a potential undersupply or even conflicts for some parts of the population. Crowding and undersupply may act as barriers to using a specific green space. This could result in less sustainable behavioral coping strategies when residents (or families) start using green spaces farther away (Arnberger 2012). Including a detailed quantity component (within parks) can help urban planners decide where to implement and improve existing green space structures, thereby relieving barriers and mitigating potential conflicts.

In terms of the equal provision of UGS and related quality criteria, public green spaces should not only be available but also need to be accessible to different groups of citizens irrespective of their location (distributional justice), age, sex, social, or ethnic status (social justice; Wright Wendel et al. 2012, Kabisch and Haase 2014, Fischer et al. 2018). We incorporated this justice component with suitable indicators (e.g., standard ground value in neighborhood or distance to public transport) and an assessment of the spatial distribution of qualitatively differentiated UGS (cf. Fig. 8).

In addition, we provide free and interactive access to our spatially explicit park indicators and quality scores through an online map application that can serve to explore (potentially unequal) UGS supply and may be used as a decision support tool for various target groups such as urban planners and decision makers or distinct residential groups such as families looking for accessible but also suitable green spaces, e.g., by providing play or sports facilities but also little impairment through traffic emissions. This is particularly relevant because a comprehensive spatial information system for parks is lacking for the city of Leipzig. Hereby our study can contribute to reduce barriers for potential

park users and eventually help to better realize the benefits of parks. In the light of more frequent and severe heat and drought events in our study area but also elsewhere such readily accessible information might be key to mitigate risks for health and well-being particularly of vulnerable groups such as children and the elderly (EEA 2016, Kabisch and Kraemer 2020).

In the case of Leipzig, we found mainly small parks of one ha or less that complement the extensive riparian forest area that runs through the city. We also found that large parks are mostly directly connected to larger green space areas such as forests (Fig. 2). Applying our set of indicators, we showed that small parks are particularly well structured in terms of green and built elements but are also often embedded in beneficial neighborhoods that promote potential park use. This highlights the importance of small UGS units in dense residential areas as places for recreation and socializing but also as local habitats and ecological stepping stones throughout the city (Peschardt et al. 2012, Brunbjerg et al. 2018, McDonald et al. 2018). We also identified spatial gaps in green space supply where residents have no or limited access to publicly managed parks because they live far away. These gaps might be compensated through other accessible green spaces, such as forests or cemeteries. Certain quality aspects and services, however, are specifically provided by public parks and are hard to compensate for, e.g., legal off-leash dog run areas, barbecue areas, diverse (public) playgrounds and sports facilities, and the presence of lighting. Finally, we demonstrated that contextual measures are of particular importance for park quality and represent feasible leverage points for improving the quality of parks, especially when available space or funding for park restructuring is limited.

Limitations and outlook

Because our study relies on available secondary data, we had to address some quality issues with the input data (cf. Appendix 1, Table A1.1). Although remote sensing (the elevation data used for our terrain indicator) and remote sensing-derived data (e.g., Banzhaf and Kollai 2018, GeoSN 2018a) provide a high degree of objectivity, spatial accuracy, and completeness, we observed issues of completeness and consistency in the data from OSM. The fact that OSM data are highly dependent on voluntary contributors (and their interests and activities) leads to highly selective map content, especially for small areas that are not detectable on aerial images or objects of minor public relevance (Girres and Touya 2010). Accordingly, we found data gaps for smaller facilities within parks (e.g., benches, waste bins, bike racks) that led to the underestimation of the related indicators and hence a decrease in the overall built-elements score for the park in question. These gaps could be closed if official data were available for such park elements, which was not the case in our study. However, for other objects, such as path networks and public transport stations, we observed an overall high completeness and spatial accuracy of the OSM data, which is consistent with the findings of Girres and Touya (2010) and Neis et al. (2012). In addition, the tree cadastral data provided by the City of Leipzig were incomplete, i.e., some parts of the public green spaces have not yet been mapped, which affected the tree species indicator in 47 parks (19%) in our study (cf. Fig. 8, the park with 2nd lowest quality score). In general, the data we received from the city administration were limited to the city area. Thus, the related indicators (e.g., that for the surrounding

population) were not complete for some parks located adjacent to the city boundary.

We also acknowledge that UGS quality assessments are complex and cannot be fully comprehensive. In this regard, our approach of linking selected indicators to ES may seem simplistic but still provides a detailed and as comprehensive as possible list of indicators to assess diverse aspects of UGS quality. As outlined in the definitions and methods section, our approach focused on public parks in a German city, representing one structurally and legally consistent and comparable type of UGS embedded in a Central European socio-cultural setting. However, assessing other UGS types and/or other geographical regions with our approach is possible through, e.g., selecting a subset of indicators or adding additional elements such as access restrictions (e.g., in the case of cemeteries or other regions) and considering other relevant specific local aspects such as public participation, design, and maintenance (cf. Fischer et al. 2018, Vierikko et al. 2020). Furthermore, an additional weighting of indicators could be applied when required by a specific setting that is different from our example.

In addition, some aspects of UGS quality may be hidden in more detail and were not fully addressed in this study, e.g., suitability and accessibility issues related to park entrances and the surface of paths, particularly for mobility-impaired people; specific playground equipment; or maintenance issues regarding waste treatment or park damage. All these factors potentially determine UGS use and visitation patterns and may act as barriers to visitors (Sreetheran and van den Bosch 2014). Due to the lack of data, we could not assess lighting in parks, which is an important influencing factor for usability at night and for safety reasons (Sreetheran and van den Bosch 2014, Hunter et al. 2019) that nonetheless has potentially negative ecological impacts (Sanders et al. 2021).

The justice components included in our approach could be further extended toward deepening the analysis of barriers and equal provision, e.g., by including socioeconomic characteristics of the neighborhoods such as age or income. Within one city, there are a variety of social and cultural aspects that influence actual park use and related potential usage conflicts, e.g., between dog owners and families or between generations, which are not fully covered by our UGS quality indicators. Moreover, assessing actual use patterns and related issues would require different approaches and data sources such as assessing user-generated geographic information, e.g., through social media or sports tracking (Hamstead et al. 2018, Heikinheimo et al. 2020). However, Heikinheimo et al. (2020) also showed that identifying the “who is going to parks” and “why” requires more detailed assessments based on social science and in situ methods, such as the studies performed by Kabisch and Kraemer (2020) and Palliwoda et al. (2020). Our indicator approach can, however, serve as a starting point for future study designs such as the streamlining of in-depth surveys on actual use of UGS.

CONCLUSION

We examined the case of Leipzig, Germany, to introduce a novel approach for assessing the quality of public urban green spaces (parks) at the city level using a comprehensive set of indicators based on available, ready-to-use data. We advanced previous research by systematically incorporating the context dimension, i.e., considering how parks are embedded in their built, social,

and natural environment. Detailed measures of the quantities of structural elements in parks allowed for differentiated assessments of the quality of parks. We presented a scoring approach for green space quality that can be used to identify spatial as well as qualitative gaps and improvement potential that may support urban planning in the context of urban green space development projects. In the case of Leipzig, we found that mainly smaller parks provided the highest indicator values and quality scores, indicating that they serve as important green spaces in the dense inner-city areas and complement the city's extensive forests, which are available around the built-up area. When assessing the potential for improving the quality of parks, we mainly identified context measures as being the most needed but also as feasible leverage points for management interventions, e.g., through traffic reduction or better connections to public transport. Our approach is comprehensive for the case of urban parks in a Central European context but is flexible enough to allow for adaption to other urban green space types and regions. Depending on the specific case, weighted or different sets of indicators may be more suitable and could be complemented by additional aspects. Furthermore, our proposed UGS quality indicators can be applied in detailed ecosystem service assessments or models.

Responses to this article can be read online at:

<https://www.ecologyandsociety.org/issues/responses.php/12485>

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Data Availability:

The data that support the findings of this study are openly available at <https://doi.org/10.5281/zenodo.4109697>.

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Appendix 1.

Supplementary information including two tables. Table A1.1 giving overview of the data used for the study, Table A1.2 giving details on the park quality indicators.

Table A1.1. List of data used to derive park quality indicators and its characteristics. Acronyms used: MMU = minimum mapping unit (for categorical vector data)

| Data denotation | Source | Type | Availability | Spatial resolution (cell size/MMU) | Spatial coverage | Time reference | Quality† | Input for Indicator |
|--|-------------------------|--|--|------------------------------------|-------------------------|----------------|----------|--|
| Outline of public green spaces | City of Leipzig 2018 | spatial, vector (polygon) | Upon request | < 1 m ² | City of Leipzig | 2018 | high | Area, Shape |
| Land cover data (incl. trees, shrubs, grass) | Banzhaf and Kollai 2018 | spatial, raster | Open (https://doi.pangaea.de/10.1594/PANGAEA.895391) | 0.6 m | City + > 1km buffer | 2012 | high | VegTotal, VegBal, TreeH, VegConf, VegNear |
| Digital landscape model (Basis-DLM) (=Land use data) | GeoSN 2018b | spatial, vector (polygon, line, point) | Open (https://www.geodate.n.sachsen.de/landschaftsmodelle-3991.html) | 1 ha (for polygons) | Federal State of Saxony | 2018 | high | Water, Stream, WaterNear, SGV, PopDay, Intensity, Urbanity |
| Digital elevation and surface model | GeoSN 2018a | spatial, raster | Open (https://www.geodate.n.sachsen.de/digitale-hoehenmodelle-3994.html) | 2 m | Federal State of Saxony | 2012 | high | Terrain, TreeH |
| Tree cadastre data | City of Leipzig 2018 | spatial, vector (point) | Upon request, partially open (https://opendata.leipzig.de/dataset/strassenbaumkataster) | Individual tree level | City of Leipzig | 2018 | medium | TreeDiv |

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|---|--|----------------------------------|---|--------------------------------|-----------------|------|--------|----------------|
| Edible plants (fruit trees and shrubs, herbs) | Terra Concordia 2019 | spatial, vector (point) | Upon request (free view under https://mundraub.org/map) | Individual plant or site level | City of Leipzig | 2018 | medium | Edible |
| Playgrounds and sports facilities | City of Leipzig 2018 | spatial, vector (polygon) | Upon request | Individual playground level | City of Leipzig | 2018 | high | Play, Sport |
| Playgrounds and sports facilities | OpenStreetMap contributors 2019 (leisure: pitch, playground) | spatial, vector (polygon, point) | Open (http://overpass-api.de/api/) | Individual playground level | worldwide | 2018 | high | Play, Sport |
| Path network | OpenStreetMap contributors 2019 (highway: cycleway, footway, path, pedestrian, track) | spatial, vector (line) | Open (http://overpass-api.de/api/) | Path sections | worldwide | 2018 | high | Path |
| Cultural, historic & ornamental elements (artwork, fountain, memorial, tomb, flower beds) | OpenStreetMap contributors 2019 (amenity: fountain; tourism: artwork; historic: archaeological_site, memorial, ruins, tomb; leisure: garden) | spatial, vector (point, polygon) | Open (http://overpass-api.de/api/) | Individual element level | worldwide | 2018 | low | Cultural, Orna |
| Sitting facilities & waste bins | OpenStreetMap contributors 2019 (amenity: bench, waste_basket) | spatial, vector (point, line) | Open (http://overpass-api.de/api/) | Individual facility level | worldwide | 2018 | low | Sit, Waste |
| Dog parks / free run areas | City of Leipzig 2018 | spatial, vector (polygon) | Online view available via ArcGIS online | NA | City of Leipzig | 2019 | high | Dog |

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|----------------------------------|---|----------------------------------|--|---|-----------------|------|--------|-----------|
| Toilets, food and drink services | OpenStreetMap contributors 2019 (amenity: restaurant, cafe, pub, fast_food waste_basket, toilets) | spatial, vector (point, polygon) | Open (http://overpass-api.de/api/) | NA | worldwide | 2018 | medium | Food, WC |
| Bicycle parking racks | OpenStreetMap contributors 2019 (amenity: bicycle_parking) | spatial, vector (point, line) | Open (http://overpass-api.de/api/) | Individual facility level | worldwide | 2018 | low | Bike |
| Public transport stations | OpenStreetMap contributors 2019 (highway: bus stop; railway: tram stop, halt, station) | spatial, vector (point, polygon) | Open (http://overpass-api.de/api/) | Individual station level | worldwide | 2018 | high | PubTrans |
| Noise data for cars and tram | City of Leipzig 2018 | Raster | Upon request | 10 m | City of Leipzig | 2012 | high | Noise |
| Noise data for railway | BKG 2018 | spatial, vector (polygon) | Open (http://laermkartierung1.eisenbahnbundesamt.de/mb3/app.php/application/eba) | Level of constant noise level (Isophones) | Germany | 2017 | high | Noise |
| Standard ground value (SGV) | City of Leipzig 2018 | spatial, vector (polygon) | Upon request | Properties of constant SGV | City of Leipzig | 2016 | high | SGV |
| Traffic emissions (NOx, PM2.5) | City of Leipzig 2018 | spatial, vector (line) | Upon request | Road sections | City of Leipzig | 2017 | high | Pollution |
| Population data | City of Leipzig 2018 | thematic, table | Upon request | Statistical block level | City of Leipzig | 2018 | high | Pop |

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|-----------------|------------|---------------------------------|---|-----------------------------|---------------------------------|------|-----|
| Protected areas | LfULG 2018 | spatial, vector (polygon) | Open (https://www.natur.sa-chsen.de/schutzgebiet-e-in-sachsen-7050.html) | Units of protected areas | Federal State 2018 of Saxony | high | PAI |
|-----------------|------------|---------------------------------|---|-----------------------------|---------------------------------|------|-----|

† Quality refers to a broad evaluation regarding criteria of thematic reliability as well as spatial accuracy and completeness

Table A1.2. Details on green space indicators. Acronyms used: SD = standard deviation.

| Indicator | Acronym | Unit | Input data† | Short description | Data processing workflow‡ |
|------------------------|----------|------|--|---|---|
| Area | Area | ha | Outline of public green spaces | Total area of park (size) | Calculate area (a) of selected parks (min. size 0.25 ha) |
| Shape index | Shape | - | Outline of public green spaces | Deviation from circle shape (SI = 1) | Calculate perimeter (p) of selected parks, calculate shape index (Forman and Godron 1986): $SI = p / (2 * \sqrt{\pi * a})$ |
| Terrain index | Terrain | - | Digital elevation model | Mean value between normalized SDs for slope and elevation | Create slope raster, calculate standard deviation (SD) of slope within individual green spaces, calculate SD of elevation per hectare of green space, normalize both SD (0 - 1), calculate mean of both normalized SD values (=Terrain index) |
| Total vegetation cover | VegTotal | -(%) | Land cover data | Proportion covered by vegetation | Sum of proportions of tree, shrub and grass cover within green spaces |
| Vegetation balance | VegBal | - | Land cover data | SD of proportions for vegetation types (trees, shrubs, grass) | Standard deviation (SD) of proportions of tree, shrub and grass cover (0 = totally balanced, 0.5 = totally unbalanced/only one vegetation type), normalize SD (0-1), reverse values (1-normalized SD) |
| Mean tree height | TreeH | m | Land cover data, Digital surface model | Mean height of tree coverage | Calculate mean height (surface model) of area under tree cover |

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|---------------------------|---------|-------|--|--|---|
| Shape index of vegetation | VegConf | - | Land cover data | SI of combined tree and shrub coverage | Merge tree and shrub cover polygons, calculate SI (cf. Shape Index) for these polygons within individual green spaces |
| Water cover | Water | - (%) | Digital landscape model | Proportion of water bodies (on the ground) | Rasterize landscape model with 1 m cell size, calculate area and proportion of lakes and ponds within each green space |
| Stream density | Stream | m/ha | Digital landscape model | Stream/ditch length per ha | Calculate total length of streams or ditches per green space and divide by area |
| Tree diversity | TreeDiv | No/ha | Tree cadaster data | Number of tree species per ha | Calculate total number of (unique) tree species per green space and divide by area |
| Edible plants | Edible | No/ha | Edible plants (fruit trees and shrubs, herbs) | Number of sites of edible plants per ha | Calculate total number of mapped sites for edible plants per green space and divide by area |
| Path density | Path | m/ha | Path network data (OSM) | Length of all tracks/paths per ha | Calculate total length of paths per green space and divide by area |
| Playground density | Play | No/ha | Playground data from administration and OSM | No of playgrounds per ha | Complement data from administration with information from OSM, manually evaluate quality of spatially distinct playgrounds using very-high-resolution aerial images (multiple playground counts had to show sufficient individual quality, e.g. a mere sandbox would be not enough to count as an additional playground), record playground number per green space, divide by area |
| Sports facilities density | Sport | No/ha | Sports facilities data from administration and OSM | No of sports facilities per ha | Complement data from administration with information from OSM, manually evaluate quality (type of sport) of sports facilities using data descriptors and very-high-resolution aerial images (every possible type of sport counted as a single sport facility, i.e. multi-functional court, e.g. for streetball and football, counted multiple), record sports facility number per green space, divide by area |

| | | | | | |
|--------------------------------------|----------|-------|---|---|---|
| Sitting facilities density | Sit | No/ha | Sitting facilities data (OSM) | No of benches per ha | Count total number of sitting facilities (benches) per green space and divide by area |
| Cultural & historic elements density | Cultural | No/ha | Cultural & historic elements (OSM) | Sculptures, monuments, memorials, archaeol. sites, fountains per ha | Count total number of artwork, memorials, tombs, archaeological sites and fountains per green space and divide by area |
| Ornamental plants/flower beds | Orna | - (%) | Ornamental elements (flower beds) (OSM) | Proportion of flower beds | Calculate proportion of flower beds for respective green spaces |
| Dog parks | Dog | - (%) | Dog parks / free run areas | Proportion of dog park area | Manually digitize dog parks from online map, calculate proportion of dog parks for respective parks |
| Waste bin density | Waste | No/ha | Waste baskets (OSM) | Waste bins per ha | Count total number of waste bins per green space and divide by area |
| Toilets density | WC | No/ha | Toilets (OSM) | No of public toilets (incl. 50m surrounding) per ha | Count total number of toilets within and including a 50-m buffer zone around green spaces, divide number by area |
| Bicycle parking density | Bike | No/ha | Bicycle parking racks (OSM) | No of bike rack sites (incl. 10m surrounding) per ha | Count total number of bicycle parking sites within and including a 10-m buffer zone around green spaces, divide number by area |
| Food/drink service density | Food | No/ha | Food and drink services (OSM) | No of food/drinks services (incl. 50m surrounding) per ha | Count total number of restaurants, fast food, bars, cafes and pubs within and including a 50-m buffer zone around green spaces, divide number by area |
| Distance to public transport | PubTrans | m | Public transport stations (OSM) | Distance to next public transport station | Calculate distance from the edge of green spaces to the nearest public transport station (shortest distance) |
| Noise | Noise | dB | Noise data for cars, tram and railway | Mean value of max. noise values for cars, tram or railway | Create raster (10 m pixel) with overall maximum noise values (over all three traffic types and for day and night), calculate mean value for individual green spaces |

| | | | | | |
|------------------------------|-----------|--|---|---|---|
| Near water | WaterNear | - (%) | Digital landscape model | Water area within 100 m buffer | Calculate proportion of water bodies within the (external) 100-m buffer zone around green spaces |
| Standard ground value | SGV | €/m ² | Standard ground value data and digital landscape model | Mean standard ground value for residential area within 500 m buffer | Select SGV data for residential and mixed areas (in digital landscape model) and calculate mean value (spatial mean) within the (external) 500-m buffer zone around green spaces |
| Traffic/emission exposure | Pollution | g/m ² *a*ha (gram per meter, year, hectare) | Traffic emissions (NOx, PM2.5) | NOx and PM2.5 emissions within 50 m buffer per ha | Rasterize source data (vector line data) with 1-m pixel size, sum up all pixels that fall within the park area plus 50-m buffer around, divide by area of green space |
| Surrounding population | Pop | No/ha | Population data on statistical block level | No of residents within 500 m buffer per ha park area | Convert population data per statistical block to a 1-m raster with resident numbers per square meter, count these pixels within 500-m (external) buffer zone around green spaces and divide by area |
| Surrounding commercial area | PopDay | - (%) | Digital landscape model | Area for commercial use and public amenities in 500 m buffer | Calculate proportion of commercial and mixed areas within the (external) 500-m buffer zone around green spaces |
| Usage intensity | Intensity | No/ha | Population data on statistical block level, Digital Landscape Model | Pop indicator weighted by available UGS alternatives in 500 m buffer | Calculate proportion of any kind of public green spaces within the 500-m buffer around parks (incl. forest, cemetery, sports areas, shrubland, other parks) (=GS_500mBuf), multiply Pop indicator with reversing value of the green space proportion: Pop*(1- GS_500mBuf) |
| Surrounding shrubs and trees | VegNear | - (%) | Land cover data | Proportion of trees and shrubs within 500m buffer | Calculate proportion of combined tree and shrub cover within 500-m buffer around parks |
| Urbanity index | Urbanity | - (m) | Digital landscape model | Distance to edge of built-up area weighted by distance to city center | Calculate distance to built-up area and rescale to positive values only (x + overall max value), calculate distance to city center, normalize distance to city center from 1 to 2, weight (=divide) |

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|----------------------|-----|-------|-----------------|--|--|
| Protected Area Index | PAI | - (%) | Protected areas | Weighted (by IUCN cat.) proportion of protected area | rescaled distance to built-up area by normalized distance to city center values, normalize weighted value (0 to 1) Calculate proportion of protected area, weight proportions by IUCN category: $PAI = (Share_IUCN_III*3) + (Share_IUCN_IV*2) + (Share_IUCN_V)$ |
|----------------------|-----|-------|-----------------|--|--|

† Note: The outline of green spaces data served as input data for every indicator by delineating the target study objects, the green spaces as such

‡ All processing done in ArcGIS Pro, v2.5

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Appendix 2. CSV file containing full list of parks assessed in this study including all 33 indicators and additional non-normalized (absolute) values of selected park elements.

[Please click here to download file 'appendix2.csv'.](#)
