Computers, Environment and Urban Systems 89 (2021) 101687

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

Which city is the greenest? A multi-dimensional deconstruction of city rankings

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ARTICLE INFO

Keywords:
Urban green
Remote sensing
Spatial metrics
City ranking
Comparative urban research

ABSTRACT

The question "*which city is the greenest*" sounds trivial, but in reality, this question contains statistical ambiguities. In this study, we approach this issue by ranking cities by green space shares. However, we do not base our ranking only on one green parameter and the commonly used administrative boundaries. Instead, we broaden access to rankings through several approaches: First, we calculate two parameters, i.e. green space shares and green space per capita. Second, we apply these parameters for two cases: for all green areas as well as for green areas with a minimum size of one hectare. The latter are considered to have an impact on near-home recreation and the local climate. Third, we relate these parameters on the one hand to administrative spatial units constituting the entity 'city', but juxtapose these on the other hand with two alternative spatial reference units: a morphological spatial unit that closely encompasses the built-up pattern of the city, and a standardized buffer unit around the city centers. The variability of these manifold rankings obtained by this study makes clear: the rank of one city in a relational system to other cities depends strongly on these parameters and spatial units applied. In our experiments we rank and compare the 80 major cities in Germany. The diversity of results allows to discuss the susceptibility of spatial statistics to ambiguities that may arise from the use of different concepts. By integrating these multidimensional concepts into one final ranking, we propose a strategy for a more holistic and robust approach while revealing uncertainties.

1. Introduction

Cities have always been in competition with each other. In times of globalization, positioning a city in this competitive environment has become increasingly important (e.g. Begg, 1999; Hall, 1995). Cities compete and seek to attract global businesses, investors, tourists and capital (Giffinger, Haindlmaier, & Kramar, 2010). One popular tool, which gives expression to this competition, are city rankings. Cities are compared, for example, according to certain key figures: e.g. by population (UN, 2018) or economic turnover (Sassen, 2019), by spatial specifications of key figures (e.g. by urban populations (Melchiori et al., 2018) or by areal extents (Taubenböck et al., 2019)), or by multi-indicator analytics (e.g. done by consulting companies such as Resonance Consultancy, 2020; The Economist Intelligence Unit, 2019; Mercer Consulting, 2019). Rankings are in the vernacular and practices quasi constitutive of the rules of the game of urban competition, to which players must inevitably adhere (Bok, 2021). It has become an advantage in the competition for perception to give the city a trademark that stands for a definable quality or for uniqueness (Löw, 2008). These attributes often aim to capture the particular character of a city, framing it as dynamic, cosmopolitan, traditional, ecologic, green, among others.

However, city rankings are not without controversy. McManus (2012) urges to critically question who produces rankings, what goal they serve, which cities are addressed, which indicators are used and how they are calculated and weighted, and how results are interpreted. A veritable industry with well over 500 different urban benchmarks has more or less taken on a life of its own (Acuto, Pejic, & Briggs, 2021). City rankings, however, are conceptually and methodologically demanding, and often lack transparency, empirical basis or data appropriate for comparison (White & Kitchin, 2021). In this paper, we want to follow Acuto et al.' (2021) call to engage conceptually, methodologically and empirically with city rankings, as critical urban research must bring more than "*limiting itself to criticism*". We aim to respond to Derudder and van Meeteren's (2019) call to engage with 'urban science', to

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https://doi.org/10.1016/j.compenvurbsys.2021.101687
Received 17 March 2021; Received in revised form 30 June 2021; Accepted 5 July 2021
Available online 13 July 2021

experiment with methods to better assess current urban conditions by the use of technology-based quantitative analysis. In this sense, our goal is to objectify a ranking through a multi-layered approach based on remotely sensed data, without denying the ambiguities of statistics.

One strategy to give the city a positive image is to highlight statistics of spatial indicators. Green spaces, as an example, have widely positive connotations in society. In Germany, for instance, the cities of Berlin, Bonn, Halle (Saale) or Hanover take advantage of this and use the adjective *'green'* in relation to their city to build a positive image. Hanover even promotes itself as Germany's greenest city. This branding, however, remains statistically unquestioned, as long as this interpretation is accepted as plausible by society. It is precisely this unquestioned aspect that we examine in this study and which we underpin with quantitative statistics on urban green space shares. For this purpose, we present multiple approaches of city rankings of the proportion of green spaces in major German cities. On the one hand, this allows to show to what extent the described perception of these four exemplary cities is also statistically reliable in spatial terms. On the other hand, this allows to systematize and discuss statistical ambiguities, which is created by the choice of parameters and their conceptualization, and the spatial reference units.

In this study, we pick the parameter 'urban green' as example. Green spaces, of course, have vital relevance for cities beyond perception and branding. They play a crucial role in urban ecosystems: they allow rainwater infiltration refilling groundwater (e.g. Bolund & Hunhammar, 1999; Wolch, Byrne, & Newell, 2014) which improves resistance to flooding (Banzhaf & De La Barrera, 2017). Cooling effects (evaporation, shading, fresh air corridors, etc.) could be empirically demonstrated (Reis & Lopes, 2019) and thus the potential to mitigate the effects of climate change to which urban flora, fauna and humans are increasingly exposed (BMUB, 2017). And, they contribute to biodiversity within cities as habitats for flora and fauna (Aronson et al., 2017; BMU, 2019). Green spaces also play a crucial role for urban citizens: In this context, the material resources of a city can be seen as a foundation through which society is specifically constituted (Löw, 2008). In particular, green areas provide spaces for recreation, social interaction and physical activity that have a positive impact on the mental and physical health of humans (Bertram & Rehdanz, 2014; TEEB, 2011). They are known to reduce mortality and the risk of cardiovascular and respiratory diseases (Gascon et al., 2016; Weigand, Wurm, Dech, & Taubenböck, 2019). And, the design and quantity of greenery impacts on the visual character and perception of the urban landscape (Chmielewski, Bochniak, Natapov, & Wężyk, 2020). With it, they contribute to the improvement of life satisfaction (reduction of stress, aesthetic experiences, spiritual enrichment) (WHO, 2016).

In a world that is urbanizing at highest dynamics (Taubenböck et al., 2012; UN, 2018), a balanced combination of built and natural urban landscapes is increasingly important. With rising numbers of people living in cities, the pressure on urban ecosystems and the environment increases. Land consumption is rising, for instance, as more space is required for living, commerce or traffic. Exposure to noise or air pollution increases (Gómez-Baggethun et al., 2013; Grunewald, Xie, & Wüstemann, 2018). The more important cities become as a living space, the more important become urban living conditions. Initiatives, such as "Die Grüne Stadt" (transl. "The Green City") and public petitions (e.g. "Grünflächen erhalten" (transl. "Preserve green spaces") in Munich) show how not only decision-makers, but also the general public are becoming increasingly aware of these issues and the protection of green spaces is a key concern (Bürgerbegehren Grünflächen erhalten, 2019; Die Grüne Stadt, 2019).

In theory, a city ranking could be based on manifold parameters or methodological approaches. Qualitative studies compare or evaluate the 'urban green' e.g. by visual assessments on greening, questionnaires on subjective perception or parameters such as green quality (e.g. Ellaway, Macintyre, & Bonnefoy, 2005; Giles-Corti et al., 2005; Hoehner, Brennan Ramirez, Elliott, Handy, & Brownson, 2005). Other approaches rely on quantitative spatial parameters. Data are applied from citizen science approaches, e.g. for the assessment of resilience of green spaces (Pudifoot et al., 2021), from official governmental data or by remote sensing (Shahtahmassebia et al., 2021). A variety of measures are applied such as green space accessibility, green volume, green space proportion or green space provision (e.g. BBSR, 2018; Fuller & Gaston, 2009; Grunewald et al., 2018; Gupta, Kumar, Pathan, & Sharma, 2012; Morgenpost, 2016; Richter, Grunewald, Meinel, & Urbane, 2016).

Overall, however, it has to be stated that spatial knowledge about the green stock is still often insufficient which is an obstacle for Derudder and van Meeteren's (2019) call for experimenting with technology-based spatial analyses. On the one hand spatial data are often neither available in the necessary spatial extent, the thematic or spatial detail, the needed accuracy and consistency, nor the desired up-to-dateness. In Germany, as example, the federal area statistics based on the real estate cadaster do show parameters for green areas, but their temporal and spatial consistency and nationwide availability is currently limited. On the other hand, the spatial indicators or measurement methods, which permit an evaluation, are neither obvious nor unambiguously defined, i. e. the comparison of spatial green indicators is not trivial.

In recent years, remote sensing has become a crucial data source for the classification of green areas and it allows to work over large areas in a consistent manner (e.g. Lamchin et al., 2020; Richards & Belcher, 2020; Shahtahmassebia et al., 2021). Methods for deriving green spaces based on remotely sensed data have advanced significantly even in the complex and small-scale urban landscapes (e.g. Parmehr, Amati, Taylor, & Livesley, 2016). Approaches on very high-resolution (VHR) data with spatial resolutions of 1 m and better combined with three-dimensional data (e.g. LIDAR) allow a highly detailed recording of vegetated areas, green volume estimates or different vegetation species (e.g. Tooke, Coops, Goodwin, & Voogt, 2009). The limitation for these VHR applications is primarily the limited possible spatial coverage, due to data cost and availability. In contrast, large-scale approaches with free-of-cost data are more limited in their spatial and thematic resolution. Nevertheless, very good classification accuracies have been achieved with sensors such as Sentinel-2 (e.g. Weigand, Staab, Wurm, & Taubenböck, 2020) or Landsat (e.g. Pflugmacher, Rabe, Peters, & Hostert, 2019) using shallow machine learning techniques. Lately, new image classification methods such as semantic segmentation from convolutional neural networks have proven very high accuracies for the detection of small-scaled structures in complex urban environments (Wurm, Stark, Zhu, Weigand, & Taubenböck, 2019), and have also been successfully applied for urban green spaces (Albert, Kaur, & Gonzalez, 2017). In this study, we therefore use Sentinel-2 satellite data instead of indicators from the area statistics, which are prone to errors due to changes in the survey method. In this way, we aim to ensure comparability across cities.

In the field of spatial parameters for analyzing and comparing the green stock across space or over time, concepts, methods, thematic content, spatial reference units, among others vary. We want to illustrate these methodological particularities with the example of spatial reference units: Whatever the intended statement in studies analyzing urban green is (as done by Bertram & Rehdanz, 2014, Fuller & Gaston, 2009; Grunewald, Richter, Meinel, Herold, & Syrbe, 2016; Larondelle & Haase, 2013; Richter, Behnisch, & Grunewald, 2017 or Richter et al., 2016; Kabisch, Strohbach, Haase, & Kronenberg, 2016), in most cases indicators are developed on administrative reference units. While these units form the basis for political decision-making, in a geographic sense their historically and politically drawn boundaries do not make them an admissible basis for consistent comparisons. The modifiable area unit problem (MAUP) testifies to aggregation effects on zonal statistics as well as on size effects (Openshaw, 1983). These have been found to be scale dependent and nonstationary over space (Margulies, Magliocca, Schmill, & Ellis, 2016) and are prone to distort or even obscure reality (Taubenböck, Standfuß, Klotz, & Wurm, 2016). To address these challenges in part with respect to the example of spatial reference units, approaches have been developed to spatially separate cities from their surrounding areas in a consistent manner to provide an admissible spatial unit for cross city comparisons (e.g. Dijkstra & Poelmann, 2014; Melchiori et al., 2018; Taubenböck et al., 2019). Nevertheless, these approaches also carry conceptual challenges (e.g. border effects); a universal approach is non-existent.

Against this background, we aim in this study to systematically compare the green stock in major German cities. The focus of our interest is on the structural differences and commonalities between cities. To do so, we generally rely on classified green spaces derived from remote sensing data. In contrast to other studies, we aim to develop a city ranking that is fed by different urban green parameters and different spatial statistical perspectives. Based on a spatially variable multi-subject concept, sufficient empiricism and a consistently conducted methodology, we aim to contribute to a more holistic, reliable comparative urban research. In this way, we want to reduce the lack of empirical knowledge about the positioning of different cities in a relational field, as demanded by Löw (2008).

2. Conceptualization of the study

Green spaces are one (of many) important indicator to describe and evaluate urban living conditions and quality of life. Related statistics often serve as a basis for societal debates or political decision-making. Spatial statistics, however, are always prone to ambiguity – which parameters are used, which scale of analysis is applied, how accurate or consistent are input data, or to which spatial reference unit is the measurement referred to. And with that, we run the risk that ill-considered spatial statistics either lead to a random result or are selected specifically to achieve certain results, which are then to serve as the basis for political decisions.

In this study we build a relational reference system of cities with respect to green spaces. It is intended to offer more resilient results through multiple perspectives. Our focus is on two common parameters in this field: The *proportion of green space* and the *provision of green space* per capita. Both parameters are calculated relative to area or number of inhabitants and are thus basically suitable for comparisons of cities of different sizes. We choose the parameter 'proportion of green spaces' because a comparable study by data analysts from Morgenpost (2016) used exactly this parameter for their ranking. And we rely on the parameter 'provision of green space per capita' as it is recognized and used by the World Health Organization (WHO, 2010). Our scale of analysis is *the city level*. However, in our conception, we do not want to conceive the city (or its spatial extent) here as a given territorial unit. Rather, we vary the spatial reference units defining the city extent in order to gain a deeper understanding of green space proportions. Our starting point is on administrative reference units, which is the spatial entity that is commonly used and the legal basis for decision-making. In addition, we elicit how consistent results are when we change the spatial reference unit. For this purpose, we use a morphological spatial unit that encompasses the built space of a city and a standardized radius-based buffer unit around the center. Our input data are based on one consistent data source: *remote sensing data*. Thus, we rely on a consistent and full survey without distinguishing between public and private green spaces. The data set has a transparent assessment of accuracy and the original data sets have a high spatial resolution.

Our study focuses on the systematic comparison of cities in terms of spatial green shares. We relate cities to each other as we believe that they are a conceptually similar target entity. For this purpose, we use *city rankings* as a means of choice. In general, we imply higher spatial shares and larger entities of green spaces are related to a higher likelihood of positive effects (e.g. Arlt, Hennersdorf, Lehmann, & Thinh, 2005; Gill, Handley, Ennos, & Pauleit, 2007). On the one hand, this means that we set the city with the highest share in the ranking to one. On the other hand, we consider that the size of an urban green area is of great importance for their effects: The larger the green space, the higher its potential benefits in terms of provisioning, regulating, habitat-shaping and cultural services. With respect to climate-relevant effects, some researchers state that regulating services, such as cooling the environment, are only provided by green spaces of one hectare or more (Arlt et al., 2005; Finke, 1994). Thus, we conduct our analysis for *all green spaces per city* and in addition also only for *green spaces larger than one hectare*.

3. Study areas, geodata and spatial parameters

3.1. Study areas: major German cities

The selection of the study areas is based on the need for an up-to-date, large-area, consistent geodatabase of spatially high and thematically appropriate resolution. Since this is available for Germany (cf. Section 3.2), we include for our analysis all German cities which are 'large cities' by definition (Fig. 1). These are 80 cities which have at least 100,000 inhabitants (BBSR, 2018). The data of the German Federal Statistical Office served as a basis for the selection and they refer to December 31st 2017 (DeStatis, 2020). This population information was assigned to grid cells with a side length of 100 m in an INSPIRE compliant grid (BKG, 2020). For the spatial definition of the respective city centers, we rely on the data sets provided by the German Federal Agency for Cartography and Geodesy (BKG) (BKG, 2020).

3.2. Geodata: green spaces

In this study we rely on green spaces classified from Sentinel-2 satellite data. This data is free of cost and features area-wide coverage with a high spatial resolution of 10 m ground sampling distance. The acquisition period of the images for the classification was between 2015 and 2017, i.e. the classification is based on data that were not recorded at the same time. The classification algorithm was trained for seven thematic land-cover classes: artificial land, open soil, high seasonal and perennial vegetation, low seasonal and perennial vegetation as well as water. Artificial land relates to built-up areas, low seasonal vegetation compares to croplands, low perennial vegetation features pastures, vineyards, and orchards, high seasonal vegetation subsumes deciduous tree cover including forests and fruit tree crops, and high perennial vegetation relates to evergreen tree cover (cf. nomenclatures in alignment with Anderson, Hardy, Roach, and Witmer (1976)). Fig. 2 illustrates the classification for two sample cities, Karlsruhe and Dresden. The classification features an overall accuracy of 93.07%. Details on data, methods and results are shown in Weigand et al. (2020).

Green spaces are heterogeneous not only in their spatial distribution, but also in their phenological characteristics, as already indicated in the classification scheme. This means that a green space can be low seasonal vegetation (such as shrubland), high perennial vegetation (such as deciduous forest), among others. In our analysis, we do not differentiate here. We aggregated the various vegetation classes into one thematic class: green areas. This abstracts our input data but also makes them consistent, so that a comparison is feasible.

3.3. Spatial reference units

Typically, city rankings are based on administrative boundaries. These spatial units are crucial as they determine a clear-cut city's boundary to establish jurisdictional competence of its municipal government (Parr, 2007). Therefore, we use them as a starting point in our analysis. We rely on *administrative boundaries* as provided by BKG (BKG, 2020).

However, these administrative units form an artificial unit as they have been created by very different political and historic developments. Although often applied, they do not form a consistent and thus comparable spatial entity for city comparisons from a geographic point of view (Taubenböck et al., 2019). It has been shown that the zonation effect, i.e. a re-arrangement of a spatial reference system into different

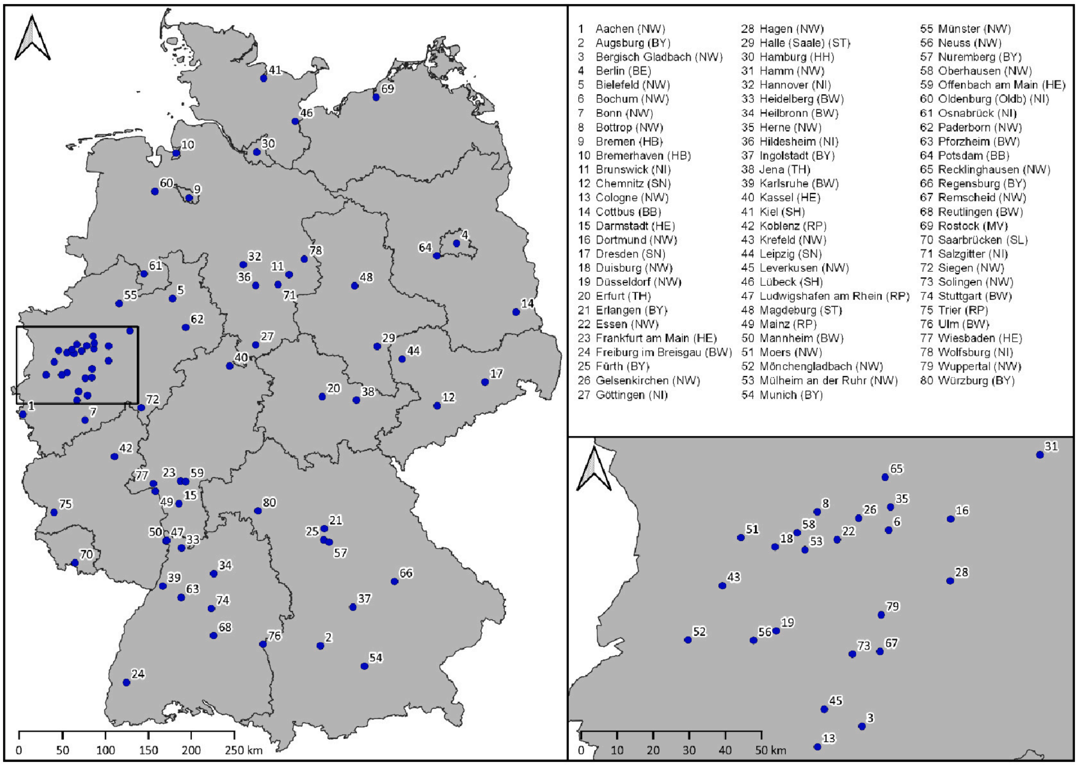

Fig. 1. Selected German cities with corresponding Federal state: BB = Brandenburg, BE = Berlin, BW = Baden-Wuerttemberg, BY = Bavaria, HB = Bremen, HE = Hesse, HH = Hamburg, MV = Mecklenburg-Western Pomerania, NI = Lower Saxony, NW = North Rhine-Westphalia, RP = Rhineland-Palatinate, SH = Schleswig-Holstein, SL = Saarland, SN = Saxony, ST = Saxony-Anhalt, TH = Thuringia.

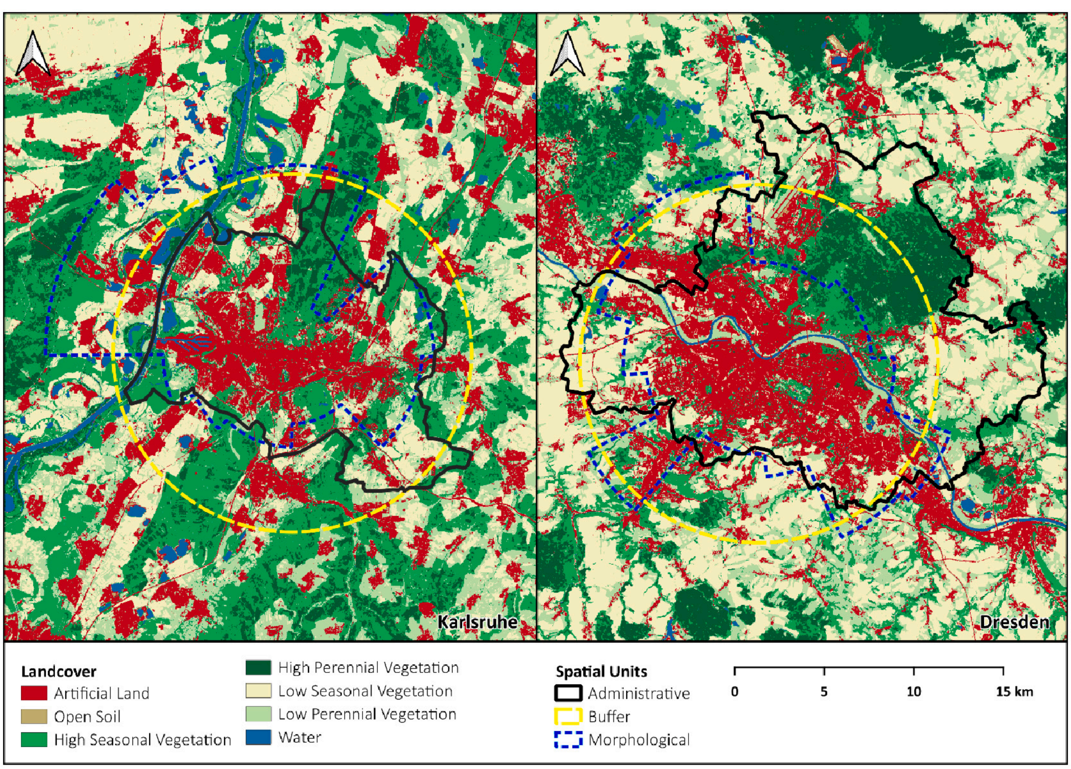

Fig. 2. Land-cover classification and three different spatial reference units delineating the entity city differently for the examples of Karlsruhe and Dresden.

units, may lead to – although based on the same initial values – different results and conclusions (Jelinski & Wu, 1996; Madelin, Grasland, Mathian, Sanders, & Vincent, 2009).

Against this background, we apply two other spatial reference units that are supposed to also mark the entity 'city': a *buffer* and a *morphologic unit*.

The *buffer unit* is understood as a uniform unit, independent of city sizes or spatial patterns. Here we apply a standardized buffer, using a 10 km radius around each city center. The selected circle and radius are here representative for other possible spatial units like squares or rectangles, or other radii. The point here is simply to incorporate a uniform size and shape as an example, as one possible variant of consistent geographic comparison. Since there are cities included in the analysis which are located in close proximity in highly agglomerated areas, such as the Ruhr area (Fig. 1), in some cases the buffer units of different cities overlap. However, in our analysis we treat each city individually, i.e. green spaces in overlapping situations are part of the analysis for both cities.

Both spatial units, the administrative and the buffer unit, do naturally not capture the morphologic settlement extent of cities in a perfect sense. Therefore, we introduce a *morphologic unit* as a third spatial entity. It is our basic assumption that boundaries of the city are conceptually difficult to determine (Sievers, 1997), but in principle they exist. To address this concretely, we apply an approach that delineates cities as a spatially coherent, comparatively dense built-up landscape. Using remotely sensed classifications on built-up structures and their density, the city boundary can be determined along an urban-rural gradient in a data-driven way (cf. for methodological details Taubenböck et al., 2019). Based on a monocentric city model, it is assumed that with increasing distance from the city center, the transition from urban to rural is along a decreasing built-up density (Fig. 2). As it is impossible to distinguish the urban from the rural according to a universal truth, the strength of this approach lies in its consistency, i.e. for all test cities the boundaries are set in a mathematically unambiguous, consistent and thus comparable manner. For some cities located in close proximity, the morphology units also do overlap. As for the buffer units, the same assumption was made, that some green spaces are part of the statistical analyses for two cities at the same time.

Fig. 2 illustrates the three spatial units that variably constitute the entity city in spatial comparison. In the example of Dresden, the administrative unit includes the Dresdner Heide, a large forest area in the north-east of the city center. The morphological boundary, in contrast, draws the border tightly around the built city and thus the Dresdner Heide is not part of the spatial reference unit – with corresponding consequences for the green share.

3.4. Spatial parameters on green space shares

In this study we apply a quantitative approach, since we rely on consistent data sets for green space shares as well as for city populations for all cities. We base our city ranking on two quantitative parameters: (1) *Green space proportion*, i.e. the share of the total green space relative to the total reference area calculated in percent. Although this metric merely reflects the quantity of green space and not its quality, it is a parameter often applied as proxy for evaluating the quality of the urban life and the ecosystem (BBSR, 2018; Faryadi & Taheri, 2009; Morgenpost, 2016). (2) *Green space provision* per capita, i.e. the total green space available for each citizen calculated in m^2 per person. This measure is often used in the political decision-making process. The WHO, for instance, calls for a minimum of 9 m^2 of urban green areas per inhabitant and defines 50 m^2 per capita as desirable (WHO, 2010).

3.5. City rankings and their deconstruction

With the two parameters on green space shares, the two-dimensional distinction according to spatial extent between all green spaces and the climate-relevant green spaces larger than 1 ha, and the three spatial reference units, overall twelve different city rankings are possible. This alone shows the diversity of spatial statistics.

In deconstructing this variability, we adopt the following rationale: We first rank the cities based on their green space shares (total and per capita), i.e. the highest share is number one. We use the city ranking based on the administrative spatial units as a starting point and analyze the deviations in the other spatial units. To show the differences between the results statistically, we determine the correlations between the approaches and describe their relationship through the coefficient of determination. We illustrate city sizes in these correlations in order to relate trends in green space shares to city sizes.

In order to identify cities with higher rank changes across spatial units, we classify them according to the comparison to administrative ranks, i.e. in those that feature above average rank losses in comparison to administrative ranks (indicated in red in Figs. 4 and 5 as well as in Figs. A and B in the Appendix), and vice versa the ones with above average rank gains (indicated in green in Figs. 4 and 5 as well as in Figs. A and B in the Appendix). The classification is based on the average of the changes in ranks for morphological and buffer units. All mean values above the respective median are classified as cities with higher changes in rank.

Rankings are naturally also based on the desire to be able to make simple and clear statements and classifications. However, the diversity of the conceptually and methodologically reasoned variety of results contains a complexity that makes a simple answer to our guiding question "which is the greenest city?" difficult. Thus, we generate a final result to meet both challenges: to abstract and simplify this complexity to make a clear statement by benchmarking cities in one final ranking, but at the same time not without quantifying the uncertainties in the process. Therefore, we merge all twelve rankings into one single ranking. To do this, we use all twelve ranks per city and list them descending over their mean value, with the lowest total in first place and the highest total in last place. We use standard deviations for the ranks to indicate the uncertainties. This way, we base the final result on all views in equal parts.

4. Results

Depending on the green parameters (green space share, green space share >1 ha, green space per capita, green space >1 ha per capita) and the spatial units (administrative, buffer, morphologic) used, results vary. First, we introduce some general results in an overview and secondly, we present the city rankings.

4.1. General results

For the aggregated results from our sample of 80 major cities in Germany, we highlight the following key statistics: For the three *spatial reference units* applied, we measure differences in size and extent. In comparison to the common administrative units, the morphological boundaries draw the city boundary more tightly around the built-up space, i.e. this reference unit is on average smaller. Specifically, 56 of our 80 sample cities are smaller, by an average of nearly 33 km^2. In contrast, the standardized buffers of 10 km radius predominantly encompass the administrative city units: 75 of the 80 city entities are larger, by an average of almost 142 km^2 more area. These differences in extent, of course, have an impact on the population figures covered by these spatial reference units. On average, over 138,000 more people live in the buffers than in the administrative units. It is remarkable that morphological boundaries, although smaller on average, still hold nearly 50,000 more people on average than administrative units. This effect is mainly related to the cities in close proximity with a continuous built landscape, whose morphological units cover areas that belong to administratively different cities.

If we now look at the parameters, i.e. the (1) *green space shares* and

(2) *green space* per capita aggregated across all cities, we measure the following differences to administrative units: (1) morphological boundaries with their smaller extents result in green space shares that are on average 6.8% lower (−7.2% for green areas >1 ha). 67 of the 80 cities have a lower green space share on this reference unit. This reveals that administrative units usually integrate more natural and close-to-nature areas around the actual built space and therefore green proportions are higher. Buffer units, although spatially very different from administrative boundaries, have similar green space shares on average (−0.4% and − 0,2% for green areas >1 ha), but basically it is distributed indifferently here. 35 cities have higher proportions and 45 have lower proportions. This shows that this spatial unit is neither adapted to the shape nor to the size of the particular city. (2) For the aggregated green space shares per capita, we see fundamental differences in the statistics: For the morphological units, the supply of green space per capita is decreasing on average by 140 m^2 per capita (139 m^2 for green areas >1 ha) (and 71 of the 80 cities have falling figures) compared to administrative units (on average 331.7 m^2). For the buffer units (on average 475.4 m^2), on the other hand, the provision per capita increases by 144 m^2 per capita (+141 m^2 for green areas >1 ha) (and 64 of the 80 cities have higher proportions).

The statistical relationship of the different parameters and spatial units generally reveal good linear fits with coefficients of determination between 0.644 and 0.784 (Fig. 3). While this may be considered a good correlation in principle, it shows that the spatial units do have a strong influence on our result. The different spatial units all have similar spatial bases, i.e. the city center and more or less the contiguous built-up areas, but they are drawn very differently at the edges of the cities, sometimes narrower, sometimes wider. And the fact that this alone is enough to have coefficients of determination of only 0.644 shows how fragile spatial statistics can be. Especially in the case of green space per capita and the morphological spatial units, we see immense deviations to lower values compared to administrative spatial units.

With regard to available green spaces, a certain relationship to the size of the city can be identified. For cities that have very high green space shares, we exclusively see low population numbers within our sample. Vice versa, the cities with large populations such as Berlin or Munich (larger cities are indicated in red and orange colors in Fig. 3) show low green shares. This inverse relationship is even more pronounced when looking at green space per capita.

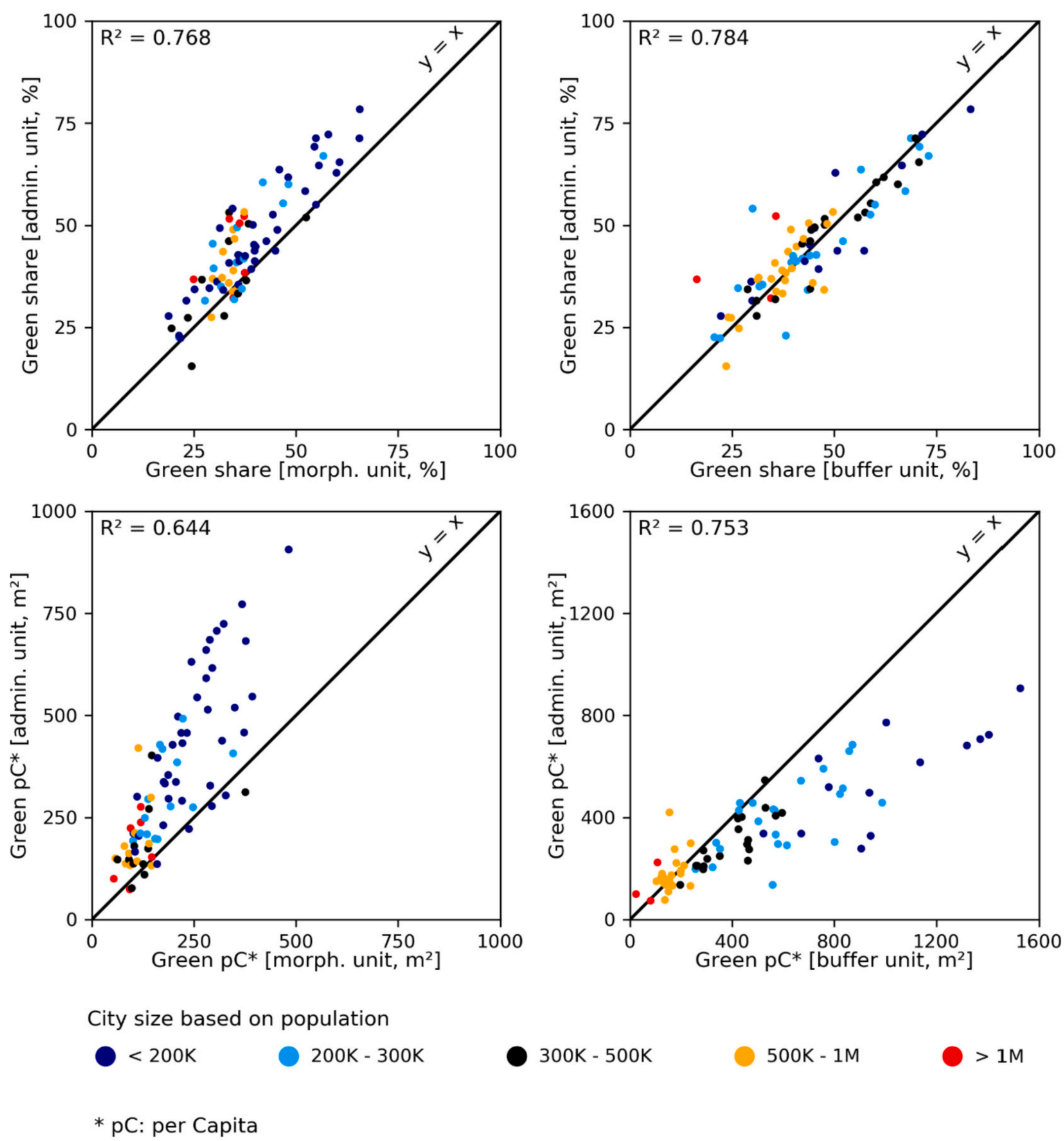

Fig. 3. Relationships of spatial green shares and green spaces per capita for morphologic and buffer units to the reference values based on administrative units. All cities are classified using population numbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. The city rankings

As variable as the parameters on urban green in relation to the different spatial units are, one thing remains indisputable according to our city ranking analyses: The city of Siegen can claim to be the greenest large city in Germany (cf. Figs. 4 and 5). In every ranking except for one, this city is ranked number one (green space shares for administrative/buffer/morphologic units: 78.4%/83.4%/65.6%; green areas >1 ha: 77.3%/82.6%/63.9%; green area per capita: 906 m^2/ 1526 m^2/ 482 m^2; green areas per capita >1 ha: 894 m^2/ 1511 m^2/ 470 m^2). Siegen is second only in the ranking of the morphologic units on green areas >1 ha, with Bergisch-Gladbach slightly overtaking Siegen with 64.0% compared to 63.9%.

The situation is more ambiguous with regard to the last place in the ranking. Here, the cities of Ludwigshafen (administrative units: green space shares 23.6%; green areas >1 ha 13.5%; green areas per capita >1 ha: 67 m^2), Munich (administrative units: green areas per capita: 74 m^2), Berlin (buffer units: green space shares: 16.4%; green area per capita: 24 m^2; green areas >1 ha: 13.6%; green areas per capita >1 ha: 20 m^2; morphologic units: green area per capita: 54 m^2; green areas per capita >1 ha: 48 m^2), and Salzgitter (morphologic units: green area shares: 18.8%; green areas >1 ha: 16.6%), alternate.

In general, we can state the range of green space shares in German cities is very uneven. To pick just two examples: the range of green area shares between 1st and 80th place is 62.9% at the administrative level, on the morphologic unit it is less with 46.8%, but still remarkably high. The tangible effects on the individual person become clear in the second parameter: the range between 1st and 80th place for green space shares per capita are 832 m^2 at the administrative level, on the morphologic unit it is with 428 m^2 again less. While this is an indication that the figures of the morphological delineation are more comparable due to the data-driven approach, we can state that green space provision across German cities varies immensely.

Fig. 4 illustrates the rankings among all 80 cities for the green space shares at administrative reference units. It reveals deviations in the ranking based on the alternative morphologic as well as on the buffer units.

Basically, it can be stated that the ranking for the different spatial units varies. It is interesting to note that 34 cities register strong changes in the ranking – 15 cities generally fall back in rankings, while 19 cities rise. For example, the city of Wiesbaden ranked 19 for green space shares on administrative spatial units (53.1%) drops by 35 ranks on morphologic units (33.6%). Or the city of Recklinghausen ranked 62 on this parameter on administrative units (34.4%) gains 27 ranks with morphologic units (36.7%). Without judging or evaluating what is true, these examples illustrate that statistics can make cities rank much better or worse depending on the calculation method.

We observe the same effects regarding the ranking based on the green spaces per capita (Fig. 5), here 35 cities register strong changes in the ranking: An extreme example is the city of Erfurt. On an administrative spatial unit, it offers over 300 m^2 of green space per capita. On a morphological unit, however, it only has 114 m^2 and falls 25 places (from 37 to 62) in the ranking. Vice versa, Regensburg is an example in the opposite direction: on morphological units this city gains 31 ranks (from 74 to 43) and increases its per capita green share from 136 m^2 to 160 m^2 compared to the statistics on the administrative level.

In the Appendix, Fig. A analogously presents the ranking for green spaces larger than 1 ha and Fig. B illustrates the ranking for green spaces larger than 1 ha per capita.

In a final attempt to create one final ranking that is as holistic as possible to abstract and simplify this complexity in rankings, we combine all the ranks of the 12 individual city rankings (Fig. 6). Thus, with regard to the two parameters 'green space shares' and 'green space provision per capita', the two variants according to spatial extent 'all green spaces' and 'green spaces larger than 1 hectare', as well as the three spatial reference units, it can be said that Siegen is undoubtedly

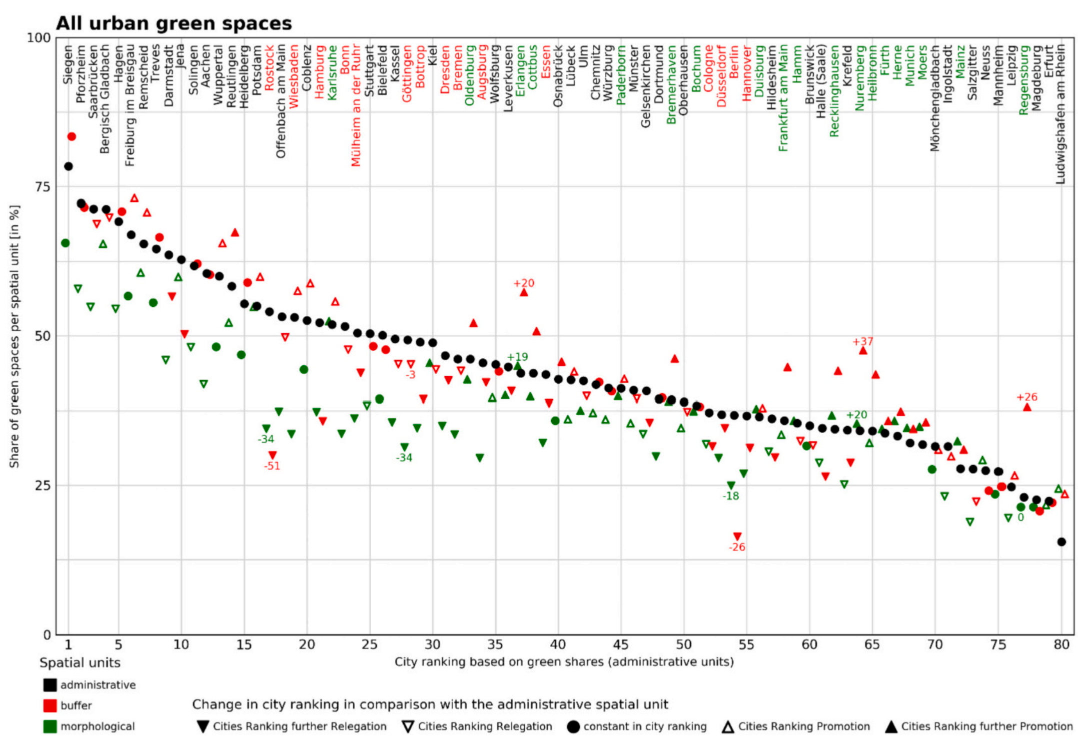

Fig. 4. Proportion of green spaces in German cities at three different spatial units: administrative, buffer and morphological. The cities are ranked along the x-axes for administrative units and deviations in the ranking are marked for the buffer as well as the morphological units. City names are classified by above average rank loss (red) and above average rank increase (green) relative to administrative units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

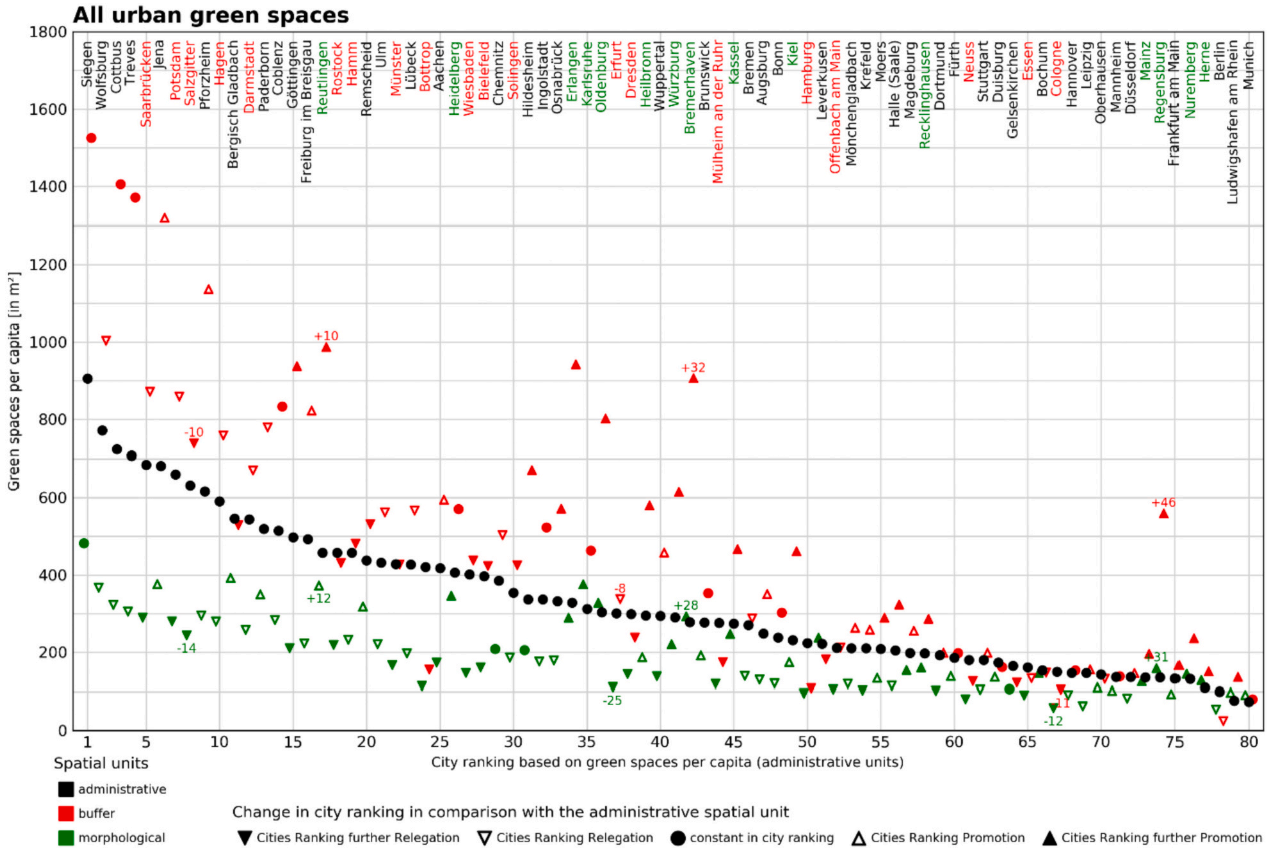

Fig. 5. Proportion of green spaces per capita in German cities at three different spatial units: administrative, buffer and morphological. The cities are ranked along the x-axes for administrative units and deviations in the ranking are marked for the buffer as well as the morphological units. City names are classified by above average rank loss (red) and above average rank increase (green) relative to administrative units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

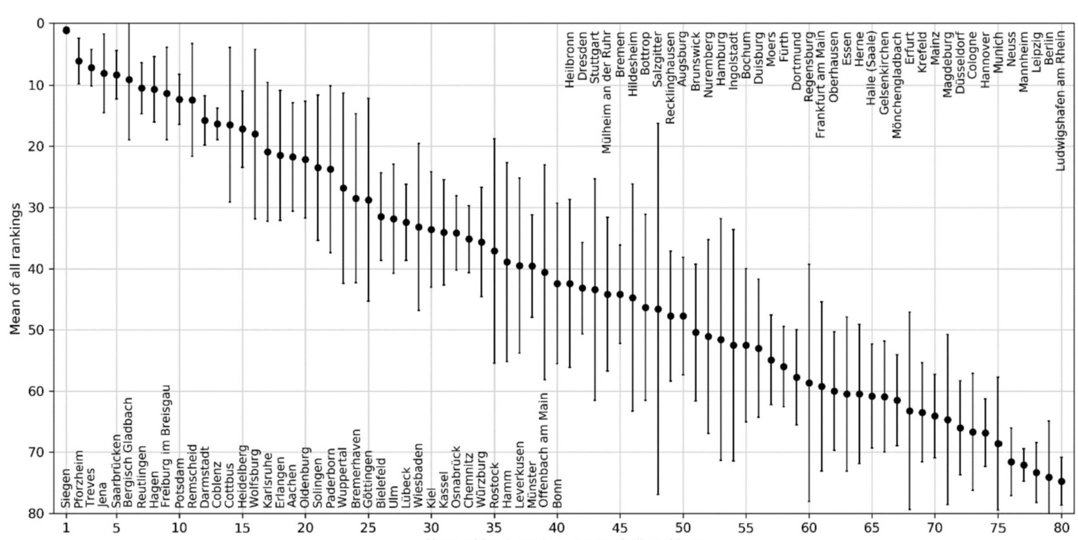

Fig. 6. Final ranking of the 80 largest German cities with respect to green area shares from the combination of all rankings and their standard deviations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and unambiguously the greenest of all large cities in Germany. This position is also reflected in the gap to the second place (Pforzheim). Ranks two to eleven are occupied by cities such as Treves, Saarbrucken or Potsdam – all of which tend to have smaller population numbers in our sample. At the lower end of the ranking we find many of the larger cities such as Berlin, Munich, Cologne or Hamburg.

Within this relational field generated from twelve rankings the probability of being subject to method-specific coincidences is lower, but the standard deviations indicate related uncertainties. For some cities the standard deviations are low or relatively low (especially at the top as well as at the lower end of the ranking). With it their positioning is generally stable and less guided by spatial statistical coincidences (e.g. Siegen, Coblenz or Mannheim). In contrast, some cities (e.g. Salzgitter, Rostock or Regensburg) feature very high standard deviations and their positioning is prone to methodological specifics. This can be taken as an indication that the local specifics, i.e. e.g. spatial patterns of the city or city sizes, must be particularly considered here for a precise estimation.

5. Discussion

In order to see one's own, comparison is required. One way of assessing oneself is within a relational system by means of a ranking. So, whether a city is well or poorly equipped with green spaces is not easy to assess in absolute terms, but to classify in comparison. However, there are a wide variety of challenges and pitfalls to permissible and meaningful comparisons. We now critically review methods and data used to compile our rankings, we reflect on rankings in general and suggest a strategy for more scientifically sound rankings, and finally we discuss the geographical results of this study.

5.1. Reflections on methods and data

As we have seen in this study, the choice of methods and data influences the resulting rankings to a not insignificant degree. In this context, we discuss the applied parameters, spatial units and accuracies of the input data.

In terms of *parameters*, we have relied on two accepted measures, 'green space shares' and 'green space shares per capita', each also according to 'all green spaces' and to 'green spaces larger than 1 hectare'. This decision is not based on the fact that these parameters are the most relevant, but rather due to the need for consistent, comprehensive and appropriate geoinformation. We are aware that these parameters can be expanded almost arbitrarily (e.g. green volumes, green space types, or quality), if the data situation allows, and that this would even create more variability in rankings. It also remains to be considered that the quantity of green spaces measured in this study, does not equal quality. In this sense, we must be aware that it is not only quantity but also the respective spatial patterns which have effects on ecological or social functions, i.e. whether green spaces are more spatially clustered, large, and contiguous or more distributed, small and dispersed.

In terms of *spatial units*, the administrative unit is crucial, as it forms the spatial basis for planning and political decisions. At the same time, the administrative entity distorts the statistics because these spatial reference units are not consistent across cities. For this reason, we have introduced morphological units. These are based on a data-driven delineation of the built environment from a remotely sensed classification. Therefore, we consider them to be a consistent spatial baseline for comparing cities. The built urban space is here predominantly more narrowly delineated around the built urban environment than administrative units and, hence, the actual amount of green space available within the built city can be determined. However, it is also clear that this approach simultaneously negates green spaces in the close vicinity of the built landscape. And, as a third, supplementary spatial unit, we have added a constant area in terms of a buffer unit of 10 km around the city center. We believe, this unit allows to determine green space shares beyond the built space and to compare them permissibly on the basis of the same extent for all cities. However, the buffer unit is very artificial because it does not take the spatial pattern or size of the city into account. Nevertheless, this unit adds an additional perspective on green space shares in space that can contribute to the overall view as done in the merged ranking. In general, we should also be aware that these two spatial units, morphologic and buffer units, could also be permuted by other radii or shapes, or by alternative spatial definitions of city centers. Effects of these variants have been shown (e.g. James et al., 2014); however, the effects to our rankings have not been tested in this study and must remain unknown. This once again demonstrates in general that the operational measurement of green space shares is subject to conceptual and methodological specifics and can therefore be manipulated.

From the perspective of our *input data*, the remotely sensed data are a consistent database and feature a generally high accuracy of 93.07%, which makes our results robust. Nevertheless, we have to note that the spatial resolution of 10-m pixels does lead to challenges in specific structural environments. In areas of large parks or forest areas, our classification even achieves higher accuracies. However, in small-scale, complex structures (e.g. detached houses with small gardens), we come up against limits with spatial resolution. Here we also measure lower accuracies. Accordingly, since many areas in cities have this complex structural composition, it can be assumed that certain measurement inaccuracies show through and have an unknown, although probably not significant, effect on our ranking.

5.2. Reflections on the rankings

Our results of various city rankings with respect to green spaces show, first of all, that there is *no absolute truth*. There is no one right parameter or no one right spatial reference unit. We argue here that achieving a higher reliability in benchmarking a city within a relational system is only possible through manifold methodological variants. And still, although the various empirical approaches presented are systematic, it is not possible to produce a simple or universally valid ranking. And it is precisely this that exposes pitfalls of rankings. In scientific literature, city rankings are often criticized, from an epistemological point of view as well as from the ideology behind them (White & Kitchin, 2021). Therefore, as critically discussed by Acuto et al. (2021), any ranking must be critically questioned in terms of how it came about, who makes it, what it represents, and who it influences.

The challenge that despite a uniform data basis and consistent calculations, rankings (in our case on green shares) vary due to the different choice of parameters or spatial reference units is shown in this work. This explains to some extent why there is neither a scientifically approved benchmark for urban green spaces nor are there generally accepted survey and measuring methods. In Germany, only some orientation values, parameters and indicators are defined for individual urban districts without general validity (BBSR, 2018). And yet, according to Kitchin, Lauriault, and McArdle (2015), rankings are attractive to practitioners because they offer a semblance of technocratic objectivity and satisfy the need for political expediency. And, rankings have become a central tool of intercity competition.

Therefore, this work intends to contribute to the objectification of rankings. We believe that the presented multi-layered ranking allows a more objective and stable positioning of cities within a relational comparison system. Through conceptual and methodological diversity, it makes rankings less susceptible to corresponding randomness and the representation of uncertainties allows to overcome absoluteness in rankings. Thus, this multi-layered approach can indicate, via uncertainties, whether local specifics need to be considered when developing interventions strategies. But we must be aware, that even this multi-layered approach cannot create complete unambiguity in the ranking. The combination of twelve variants in this work is thus intended to provide a blueprint that can be extended at any time to include additional green parameters.

The combination of the various rankings allows us to undoubtedly designate Siegen as *the greenest city in Germany*. This is first of all a confirmation of a similar result of a methodologically different study a few years ago (Morgenpost, 2016). However, only one parameter and one measurement method were used in their study. While the same study provides an equally clear result regarding the last place (Ludwigshafen), we paint a more complex picture here due to the uncertainties (Ludwigshafen, Munich, Berlin, Salzgitter). This means that secondly, in our study the challenge and the potential lies rather in the detail of data interpretation. Whether Siegen has 65,6% (morphologic) or 83,4% (buffer) green space shares or whether it provides 482 m^2

(morphologic) or even 1526 m^2 (buffer) green spaces per capita – so in fact very different values that can be attributed to a city – depends on the spatial reference unit applied. These variabilities in numbers reveal the complexity of a reasonable assessment of the situation and a good strategy of evaluation cannot emerge by a more or less randomly chosen approach, but only in a differentiated view: an evaluation that reflects conceptually and methodologically and co-evaluates local specifics in individual cases to derive appropriate recommendations for action.

And in this sense, benchmarking can be a valuable tool to develop and address constructive interventions and to contribute to the strategies of local governments (Robin, 2021). Whether and how local actors can translate this knowledge into action and to what extent rankings in general and this one in particular help to define interventions must, however, remain open at this point.

5.3. Geographical reflections

From a geographical point of view, we can generally state from our analysis that German cities are well equipped with green spaces. When we relate our results to the suggestions of the WHO calling for a minimum of 9 m^2 of urban green spaces per capita and defining 50 m^2 per capita as desirable (WHO, 2010), we see that even the cities at the bottom of the ranking are (at the administrative unit: Munich 74 m^2 and at the morphological unit: Berlin 54 m^2) equipped with even more green space per capita than desirable. For the buffer unit, the green area space per capita for the ranking tail end Berlin is 24 m^2, which is about half of what was suggested as desirable. Herein this particular case we have to consider that the 10 km radius for Germany's largest city only covers the core city. Based on its green space shares on the morphologic (54 m^2 per capita) as well as the administrative unit (100 m^2 per capita), we see the proposed minimum is far exceeded.

With respect to the four example cities from the introductory section – Berlin, Bonn, Halle and Hanover – which have branded themselves by the adjective 'green', we observe something somewhat surprising: none of the three cities is in the top 10 of our ranking or even close to it. Bonn is at rank 41 in the combined ranking, Halle at 65, Hanover, the self-proclaimed greenest city in Germany, ranks 74th, and Berlin even at the penultimate position 79. Thus, the question arises whether this attribute for branding is by any means justified. These claims can be attributed to the practice of "greenwashing" (e.g. Seele & Gatti, 2017), i.e. a form of marketing in which e.g. green statistics are used to convince the public that, in our case, the city stands out in particular. When relating our results to the marketing use, it seems that whether a city is accepted as green in the public perception seems to depend less on objective spatial shares and more on what people accept as plausible. In this sense, Bok (2021) points to the powerful influence of rankings in defining and narrating the normative conditions of discourse and practice. This is, of course, accompanied by the need for objectification.

In our rankings, we have basically assumed that a higher share of green spaces is related to a higher likelihood of a positive effect (Arlt et al., 2005; Gill et al., 2007). In this rationale, the purely quantitative approach in this study is justified, but of course, reality is more complex. We should be aware, that the distribution of green spaces reflects the importance of the local. The impact of green areas is on the space that encompasses everyday life or on cooling effects in the immediate vicinity, and that is something quite different than measured at administrative (or other) units defining the city (Löw, 2008). In addition, we should be aware that quantitatively fewer green areas do not necessarily have fewer positive effects: with suitable spatial arrangement or different types of green areas, climate-relevant effects may be achieved with less spatial quantity. For compensation in the social sphere, high quality and accessibility can be more important than quantity in certain cases. Last but not least, it must also be borne in mind that in the struggle for urban space, never only one parameter (in our case green areas) must be considered whether a city is liveable. This is always linked to the need for housing, infrastructure, culture, and much more. The fact that many of the larger cities such as Berlin, Munich or Hamburg are at the bottom of the ranking also makes the following clear: these cities are highly sought-after residential locations in Germany with highest influxes or highest (and increasing) housing prices. Their attractiveness and the perception of qualities of place and life do not seem to be influenced in the least by the lowest proportion of green space among German large cities.

6. Conclusion

The question "*what is the greenest city of Germany?*" seems to be trivial. Nevertheless, behind this supposedly simple question lies a deeper complexity. True to the motto "*don't trust statistics that you haven't faked yourself*", our different experiments on the proportion of green spaces in cities are not 'fakes', but transparent in their parameters, data and methods, and still nothing is black or white. Based on conceptual definitions, applied parameters or spatial units of measurement, a myriad of statistics which are all mathematically correct, can be produced to steer the impression one or the other way.

With this study we show how fragile spatial statistics are, but how they can then be (mis-)used for political decisions without considering the complexity of reality. However, with manifold different perspectives – according to parameters and spatial units – we believe we can contribute to a more holistic understanding for systematically approaching these issues. We argue here in the line of Derudder and van Meeteren's (2019) call to engage with 'urban science': for expanding this multi-layered ranking including related uncertainties in future scientific work by experimenting with methods and technology-based quantitative spatial analysis to better assess current urban conditions. The addition of alternative spatial approaches such as green components in the immediate surroundings of households (Wüstemann, Kalisch, & Kolbe, 2017) seems to be just as relevant as systematically integrating further parameters such as urban green accessibility, size, edges, volumes, spatial patterns or connectivity, among others to extend the suggested multi-layered concept of rankings.

As spatial thinking forces to think in difference, we believe being able to describe and understand these differences between approaches as well as between cities in their complexity in a more holistic sense. We see this as a starting point for thinking about urban developments. With this basis of good empirical knowledge within a relational system, the necessity for constructive interventions can be identified, examples of others can be studied and planning attempts can be made to overwrite or to adapt the existing structures of a city.

Acknowledgments

This study was partly funded by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) (project "Monitoring des Stadtgrüns), the German Federal Ministry of Transport and Digital Infrastructure (BMVI) (projects "meinGruen" and "SAUBER" (funding codes 19F2073B and 19F2064B, respectively)), and by the German Federal Environmental Foundation (DBU). We would also like to thank Julia Tenikl and Lennart Imberg for their support.

Appendix

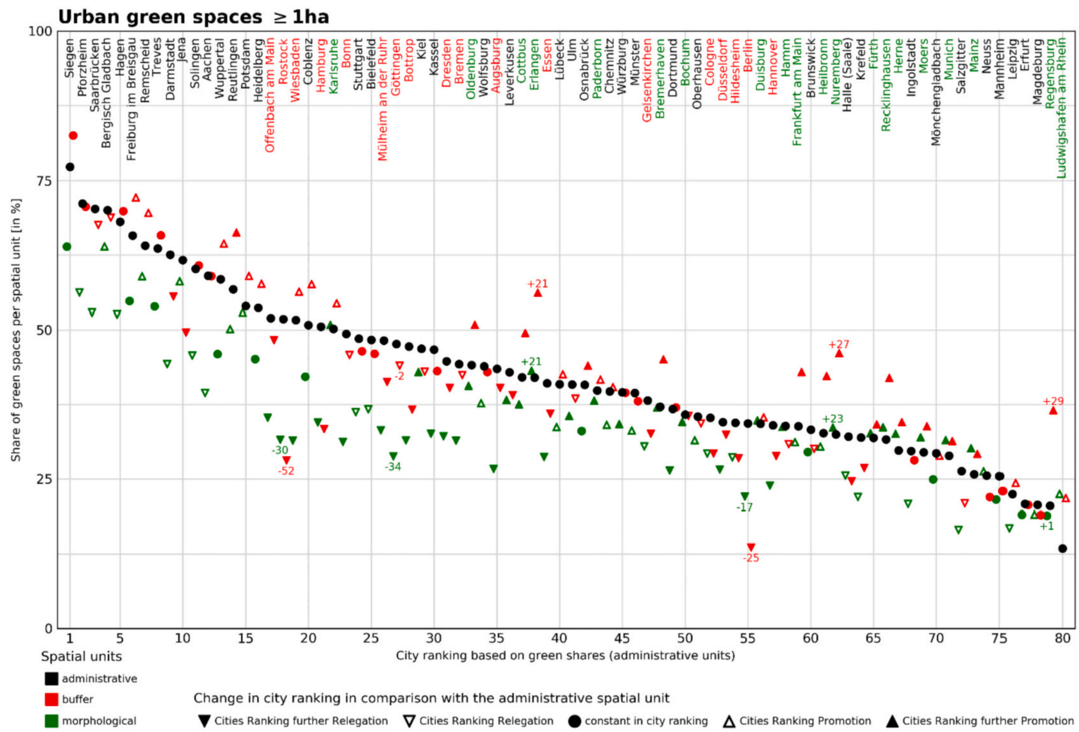

Fig. A. Proportion of green spaces >1 ha in German cities at three different spatial units: administrative, buffer and morphological. The cities are ranked along the x-axes for administrative units and deviations in the ranking are marked for the buffer as well as the morphological units. City names are classified by above average rank loss (red) and above average rank increase (green) relative to administrative units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

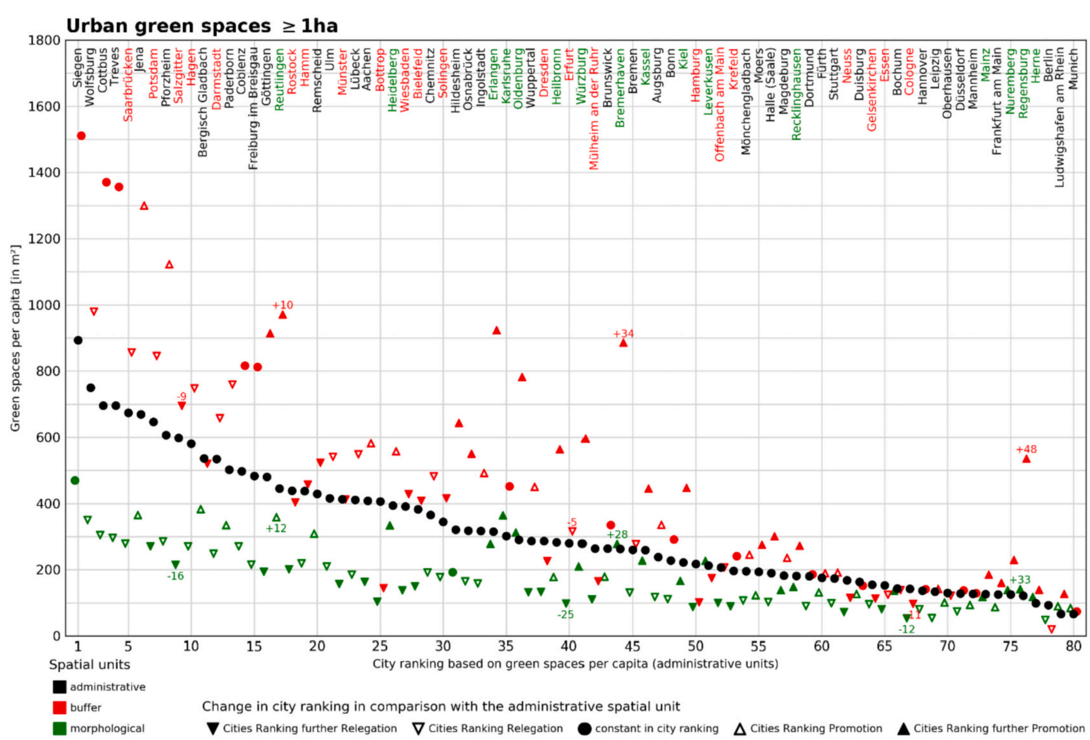

Fig. B. Proportion of green spaces per capita >1 ha in German cities at three different spatial units: administrative, buffer and morphological. The cities are ranked along the x-axes for administrative units and deviations in the ranking are marked for the buffer as well as the morphological units. City names are classified by above average rank loss (red) and above average rank increase (green) relative to administrative units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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