Computers, Environment and Urban Systems 95 (2022) 101830

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

To be, or not to be *'urban'*? A multi-modal method for the differentiated measurement of the degree of urbanization

H. Taubenböck [a,b,*], A. Droin [a], I. Standfuß [a], F. Dosch [c], N. Sander [d], A. Milbert [c], S. Eichfuss [c], M. Wurm [a]

[a] German Aerospace Center (DLR), Earth Observation Center (EOC), 82234 Oberpfaffenhofen, Germany
[b] Institute for Geography and Geology, Julius-Maximilians-Universität Würzburg, 97074 Würzburg, Germany
[c] Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), 53179 Bonn, Germany
[d] Federal Institute for Population Research (BIB), 65185 Wiesbaden, Germany

ARTICLE INFO

Keywords:
Degree of urbanization
Urban
Rural
Spatial statistics
Building density
Population density

ABSTRACT

Today, 56.6% of the world's population is urban and the trend is rising; in Germany, the urbanization process is almost complete at 80.3%. This is the ubiquitously used narrative. Surprisingly, the figures behind it are rarely questioned. The spatial statistics responsible for this meta-narrative are, however, prone to ambiguity. They suffer from a lack of systematic empirical justification, and from cross-national differences in cut-off values used to differentiate between urban and rural populations. In this study, we present an empirical approach that allows to systematically map urban and rural populations in a spatially and thematically differentiated manner using a multimodal method. On the one hand, we resort to the common approach of presenting the degree of urbanization in terms of population figures for administrative units. However, we do not only use the common national threshold value, but we project various national thresholds applied in different countries across the globe to classify multiple degrees of urbanization onto our study site Germany. On the other hand, we also calculate various degrees of urbanization at a higher spatial resolution using a regular grid. Beyond the common approach of calculating the degree of urbanization by population figures, we also apply at grid-level two additional variables: building density and the share of a certain building type. By systematically applying thresholds between minimum and maximum per variable, we trace the effects on the resulting degree of urbanization. These multiple perspectives lead us to propose that a range rather than a singular threshold allows us to estimate the degree of urbanization in a more differentiated way. To do so, we estimate the degree of urbanization for Germany on a probability-based basis. Therefore, we combine possible variants from the administrative approach using population figures and the grid-based approach using thresholds of population, building density and the share of a certain building type. Our results show that Germany can be considered urban by at least 50.0% up to possibly 68.1% of the population, which by no means comes near the reported 80.3%. We conclude that the results of the commonly used approach to quantify urban populations are not tenable in their clarity and should therefore be used only with great caution for political and societal decision-making.

1. Introduction

In the best case, we base decisions – political, social, economic, ecologic, or even personal – on facts. Science is a source of profound facts. Nevertheless, scientific knowledge is subject to uncertainties due to applied concepts, data or methods that are not always easy to interpret. There is the danger that mathematically unambiguous calculable 'facts', nevertheless lead to ambiguity or even misinformation. Therefore, appropriate interpretation and a deeper understanding of the situation is a necessity.

In spatial sciences or urban geography, to take an example, there are often gaps between computable results and their interpretation. Results based on precise mathematical calculations may lead to biased statements due to inconsistencies or inaccuracies in the input data (e.g. Malizia, 2013), the preference for a particular method (e.g. Schabenberger & Gotway, 2005) or indicator (e.g. Shearmur, 2017), or due

* Corresponding author at: German Aerospace Center (DLR), Earth Observation Center (EOC), 82234 Oberpfaffenhofen, Germany.
E-mail address: hannes.taubenboeck@dlr.de (H. Taubenböck).

https://doi.org/10.1016/j.compenvurbsys.2022.101830
Received 22 February 2022; Received in revised form 13 May 2022; Accepted 17 May 2022

to the modifiable areal unit problem (MAUP) (e.g. Openshaw, 1983). With respect to the latter, the shape and scale of aggregation units, for example, can produce a statistical bias (e.g. Taubenböck, Standfuß, Klotz, & Wurm, 2016). On the other hand, certain statistics of spatial science remain fuzzy by nature, as results depend on the defined conceptual framework, the data, the scale or the methods applied. Let's take 'polycentricity' for an illustration – a concept that grasps a hierarchical division of centers in urban space (e.g. Batty, Besussi, Maat, & Harts, 2004). Until today, there are no generally accepted indicators (used are e.g. job concentrations (Krehl, 2016), built densities (Taubenböck, Standfuß, Wurm, Krehl, & Siedentop, 2017), among others) or methods (used are e.g. threshold approaches (Kim, Yeo, & Kwon, 2014), locally weighted regression (Roca Cladera, Marmolejo Duarte, & Moix, 2009), among others) to unambiguously distinguish these centers and whether those centers distinguished define poly- or monocentricity or the state in between (e.g. Bartosiewicz & Marcińczak, 2020).

1.1. Questioning the common logic of urban population

And yet, science in the urban domain has produced seemingly unambiguous facts we all – in science, in media, in politics, among other branches – take for granted: what the largest city in the world is or what the proportion of urban population on our globe is. These are generally accepted facts. Incidentally, it is usually stated that the largest city in the world is Tokyo (UN, 2018) and, that 55.6% of the global population today is urban (UN, 2018). These figures, with few exceptions (cf. e.g. Bocquier, 2004; Buettner, 2014), are the basis of argumentation in most contributions. In this study, we question if we are already subject to a fallacy on these 'facts'?

Recent studies challenge these two types of 'facts' by trying to generate estimates with their own concepts and their own empirical investigations aiming at more reliable figures. On the *city sizes,* official statistics are challenged e.g. for Germany (Budde & Neumann, 2018) or on a global scale (Taubenböck et al., 2019). The latter study reveals that not Tokyo, as the UN (2018) has stated, is the largest city in the world, but the urban agglomeration in the Pearl River Delta in China. It is demonstrated that long-established administrative boundaries can become obsolete in times of highly dynamic urbanization. And beyond, these units are inconsistent across municipalities and thus are not acceptable as spatial comparators due to a distortion of statistics. They, in contrast, develop a method to distinguish urbanized from rural areas in a consistent manner for all cities across the globe. The advantage of this analysis lies in its spatial consistency.

1.2. Arbitrary classifications of 'the urban' and 'the rural'

On the *degree of urbanization*, scientific studies, reports, media, political statements argue that more than half of the world's population now lives in urban areas. These statements are predominately based on the most authoritative and cited source of global urbanization levels published by the UN (2018). Melchiori et al. (2018), however, claim that the widely accepted UN numbers are incorrect. Using remote sensing and population data and a consistent methodology to define the degree of urbanization, they claim that a significantly higher amount is urbanized than stated by the UN: they state that already 84% of the world is urban. This assessment, in turn, has been challenged by Angel, Lamson-Hall, Galarza, and Blei (2018). They claim that what we commonly understand as 'urban' runs counter to this analysis. Based on four arguments relating to low-density areas classified as urban, the migration aspect towards cities, the share of the labor force in agriculture and village non-farm occupations and regularities in settlement hierarchies, they argue that the world is still nowhere near as urbanized as Melchiori et al. (2018) assert.

These few examples elaborated here, together with studies e.g. by Balk, Leyk, Jones, Montgomery, and Clark (2018), Dorélien, Balk, and Todd (2013) or Liu, He, Zhou, and Wu (2014) as well as by initiatives such as the Global Rural-Urban Mapping Project (GRUMP) (Socio-economic Data and Applications Center (SEDAC), 2021) or the GHS-SMOD product of the Global Human Settlement Layer (GHSL) (JRC, 2021), show that in research studies on the degree of urbanization in particular, and in spatial sciences in general, there are often no clear, incontrovertible facts, but only different ways of measuring something and interpreting it accordingly. In the urban/rural domain, this complexity is often encountered by conceptualizations such as 'urban-rural continuum' (e.g. Champion & Hugo, 2004; National Academies of Sciences, Engineering, and Medicine, 2016; Pahl, 1966), urban-rural-interface (e.g. López-Goyburua & García-Montero, 2018) or 'urban-rural gradient' (e.g. du Toit Marié & Cilliers, 2011). Thus, the truth even viewed from a scientific lens is not easily determined and it remains tolerant of ambiguity. Brenner and Schmid (2013) name the above discussed statistics empirically untenable (a statistical artifact) and theoretically incoherent (a chaotic conception).

In this paper, we aim to take an empirical turn by applying the 'chaotic conceptions' for calculating the *degree of urbanization*. We do this using the categories '*urban*' and '*rural*' – artificial as they may be – as they are nevertheless constitutive of our society (Löw, 2008; Redepenning & Hefner, 2018), often providing an argumentative basis for political decisions. However, we believe that the widely accepted statistic that today (i.e. in 2021) 56.6% of the world's population resides in urban environments (UN, 2018) paints a superficial picture of a highly complex situation. Like the studies mentioned above, we want to challenge these statistics, or at least question the validity of these generally accepted and used facts.

In contrast to other studies, we are in no way concerned with eliciting what constitute meaningful variables or thresholds that can be used to measure '*the urban*'. Our aim is to show how arbitrary the classification of '*the urban*' and '*the rural*' can be in such statistics due to the variation of concepts, variables and thresholds. With it, we follow the call from Angel et al. (2018) to approach a more definite method by a systematization of the effects of the various methods. We do so by the example of Germany as the very good geodata situation allows us to grasp the complex situation at very high and unprecedented resolution in an empirical manner. We want to approach the statistics, i.e. the degrees of urbanization, from different spatial and thematic angles and show how susceptible these numbers are to different concepts and methods. As we believe that a single threshold value always falls short, we propose to specify the degree of urbanization in a more differentiated, probability-based way which allows a range between the clear poles 'urban' and 'rural'. With it, we want to add to the discussion that we need better data, clearer and maybe other concepts and accepted methods to make interpretations of geodata not arbitrarily reinterpretable for every desired point of view.

2. Conceptualization of '*the urban*' and '*the rural*'

In this study, as mentioned, we are not primarily interested in developing our own conception of '*the urban*' and '*the rural*'. Rather, we are interested in developing an approach that maps these two thematic classes in a more nuanced way. Thus, it is important to have a basic conceptual understanding of *'the urban'* and *'the rural'*. Generally, the core idea of the urban in distinction from the rural are various forms of higher density: Concentrations of people, of everyday' s routines, of social and economic structures, of differentiations and heterogeneity, or of built structures in one place, among other things (e.g. Nassehi, 2002; Tonkiss, 2013).

Urban as a term thereby conceptualizes two different aspects: On the one hand, it testifies to a certain way of life. Tolerance, freedom, social distance, networking, diversity, interculturalism, cosmopolitanism, open-mindedness, intellectuality, and creativity are often attributed to this lifestyle (Florida, Gulden, & Mellander, 2008; Glaeser, 2010; Tonkiss, 2013; among others). Even though these attributes are probably most constitutive in larger urban agglomerations, these are nonterritorial characteristics, or at least they are very difficult to locate in a very concrete way. The urban lifestyle is spreading spatially unspecifically in a world of increasing mobility and better communicative connectivity. In consequence, it is not what is defined as a city in administrative law that appears as urban, but what is perceived as an urban unit in everyday life (Löw, 2008). On the other hand, the term 'urban' points to the quantitative aspect of density in one place: of populations, of built structures, of infrastructure, and architecture, as well as of physical growth and structural change (Löw, 2008). In this line of thought, urban is, according to Berking (2008), first and foremost a spatial form with territorial characteristics. Even though, as discussed above, our lives are becoming more and more globally networked, we still live locally (Castells, 1996). Social life continues to be organized into coherently bounded spatial envelopes ('human settlements') whose demographic properties can be defined within spatial boundaries (Wirth, 1969). In this line of argumentation, the place of residence and its territorial design still have a considerable relevance and thus, territorial approaches remain important.

In this study, we resort to the basic concept that the *urban is a form of higher density at a place.* It is thus our basic assumption that 'the urban' can be territorialized. Although it remains conceptually difficult to determine, we assume that in principle spatial boundaries between urban and rural exist (Sievers, 1997). However, for our approach we disregard forms of density in terms of social dimensions, lifestyle, heterogeneity, etc. and focus on the density of population and built space. And fundamentally, we do not want to commit ourselves a priori to which thresholds or which definitions constitute *the urban*, since we are aware that, at the margins, the characteristics of the urban may be ambiguous or can also be understood as transition zones, urban-rural gradients or a continuum. Rather, we aim to explore the question of what influences these ambiguous distinctions have on the assessment of the degree of urbanization at national scale. And finally, we propose a method that allows these ambiguities to be presented in a more differentiated way.

3. Experimental set-up

3.1. Classification of 'the urban' versus 'the rural'

We experiment with different characterizations of '*the urban*' and its complement '*the rural*'.

For the classification the spatial unit referred to is important. Administrative units are of jurisdictional, administrative and political relevance and therefore remain a central element in any discourse. At the same time, these administrative demarcations result from historical-political processes, they are heterogenous in size, feature spatial outlines which are somehow artificial, and they may feature within their area both types, i.e. dense areas that can be attributed more to '*the urban*' as well as low dense areas that can be attributed more to '*the rural*'. A grid-based approach, in contrast, allows the variables to be positioned more in the local, i.e. they allow for a less spatially cohesive, more porous type of mapping.

Against this background, we use *two distinct spatial approaches*: (1) *a territorial approach* where we focus on classifying the official administrative units; (2) *a grid-based approach* where we focus on a standardized spatial unit determined by a grid.

On this basis, we set up our experiments as follows:

1) For the *territorial approach,* we quantify '*the urban*' vs. '*the rural*' by using threshold values to assign the administrative units of municipalities to one of the two types. We base this on the commonly used variable of population numbers. For the selection of thresholds, we use the wide variety of thresholds defining the urban (ranging according to UN World Urbanization Prospects from 200 to 50,000 people) as applied by different nations across the globe (UN, 2020) as well as the threshold of 100,000 people suggested by the study of Angel et al. (2018). Then, we calculate the proportion of the cumulative population values classified as urban in relation to the total population at national scale.
2) For the *grid-based approach,* we determine '*the urban*' vs. '*the rural*' at a spatially continuous and consistent grid of 100 $\times$ 100 m. Based on our available data, we focus here on *three variables: building density, population density* and *the share of a certain building type*.

Building density is measured as the percentage of the sum of all ground areas of buildings per grid, i.e. per hectare. *Population density* is the number of inhabitants per grid. For this specific variable, we relate the population density relative to the maximum value of population density at a grid cell in Germany to scale the variable accordingly between 0 and 100. The *share of a certain building type* is measured as the share of a particular building type per grid expressed as a percentage. Here, we assume that certain building types are characteristic of urban living. For this purpose, we make use of the following argument: When we imagine urban housing, we usually think of high-rise buildings, block development, large housing estates, or multi-family houses. In this conception, these structural appearances constitute '*the urban*', while single-family or semi-detached houses or the like do constitute a more rural way of structure.

All these variables are clearly spatially locatable. Landscape always consists of a complex web of structural types even on the here applied grid level. As we do not want to determine a priori which grid cell we categorize as 'urban' and which one we categorize as 'rural', we systematically calculate for all three variables thresholds from the minimum to the maximum in order to quantify the effects on the degree of urbanization. In the experiment, we apply the entire possible range of thresholds: in 1% steps from a minimum greater than 0% share of the respective variable to a maximum of a 100% per grid. So, as an example, we assume that in the two most extreme cases, we count a grid cell as 'urban' even if there is not a single building at all, i.e. 0% share, or we count a grid cell as 'urban' only if 100% of the area is occupied by buildings. In doing so, we determine how the degree of urbanization varies as a function of thresholds. The result is a non-contiguous spatial grid constituting '*the urban*'.

We present the variability of our results on the degree of urbanization in the form of progress plots over the thresholds. In addition, we also map the spatial effects of the various thresholds per variables on the degrees of urbanization. Of course, since a myriad of thresholds exist, we select representative examples for comparison in the cartographic representations.

3) Finally, we bring the different manifestations of the approaches together and propose a *combined, probability-based approach*. Each approach introduced above has its justification. And yet, due to the large number of variants, the evaluation of *'the urban'* versus *'the rural'* in spatial statistics falls short of expectations: a definitive statement about the degree of urbanization in Germany. We approach this definitive statement by combining the different variants without leaving aside the statistical ambiguity.

The thresholds from the various national approaches on administrative units as well as the systematically calculated thresholds of the different variables on the grid-based approach, produce different quantitative results and cartographic formations of *'the urban'* vs. *'the rural'*. Since we do not define a priori whether a certain approach is more appropriate than others, we give the national thresholds at the administrative units the same weight as the grid level variants. As there are 14 variants for the territorial approach based on national definition thresholds, we aim to match these with grid-based ones. As we have three different grid-based approaches, we select five variants each that add up to 15 variants. Of course, due to the systematic test in 1% steps of the threshold values for the grid-based approaches, there are significantly more variants per variable available than we can use if we weight both approaches equally. To guarantee a generally bias-free calculation at best, the chosen urbanization thresholds for the grid-based approaches are evenly distributed across the entire range: 1, 25, 50, 75 and 99% respectively. The sum of all 29 variants (14 administrative, 15 grid-based) allows a probability-based classification of the degree of urbanization at grid level.

In the thought process that the delineation of *'the urban'* from *'the rural'* constitutes itself not at the extremes, but somewhere around the middle, we generate for the combined, probability-based approach a three-part classification: high probability of being '*urban*' or '*rural*', as well as a '*range in between*'. By the latter class, we define the uncertainty for the quantification of the degree of urbanization. For classification, we apply the standard deviation around the median to narrow down the range. This range of uncertainty naturally has grid cells along the continuous range of probabilities that are closer to *'the urban'* or to *'the rural'*. We subclassify these again into three classes based on quantiles of population for these designated areas.

3.2. Study area and data

Our study site is Germany. The degree of urbanization for the country is given at 80.3% (UN, 2020). These statistics refer to the spatial level of municipalities with more than 5000 inhabitants (DeStatis, 2020), i.e. a territorial approach is used. Despite this apparent clarity, other approaches go beyond the simple urban-rural dichotomy. Eurostat (2021), as an example, differentiates the degree of urbanization according to densely populated (cities), medium population density (towns and suburbs), and sparsely populated (rural). At a spatial grid level of 1km^2, *'the urban'* is classified here as clusters of neighboring grid cells with a density of at least 300 inhabitants per km^2 and at least 5000 inhabitants suggesting the degree of urbanization for Germany at 69.6%. These two examples show how different approaches applying different spatial levels and different variables and corresponding thresholds cause different results. The latter conceptualization indicates that a dichotomous distinction could fall short with regard to the complexity of urban-rural gradients or continua. With our proposed classification of the degree of urbanization based on probabilities and with a range of uncertainty, we believe that the susceptibility of statistics can be mastered in a more differentiated way than with a dichotomous characterization of the territory.

We apply the different constitutions of '*the urban*' to entire Germany. We do this because here, in comparison to the continental or global input data used in the cited studies above, the spatial and thematic resolutions of the available data is particularly good and yet area-wide and consistent.

For our analysis, we use as basic data sets (1) *administrative units of Germany at the municipality level* as provided by German Federal Agency for Cartography and Geodesy (BKG) (BKG, 2020, 2) *census data* on population. Here, we rely on population data projected to 2018 based on the 2011 census from the German Federal Statistical Office. Population information is available at 100x100m grid cells (DeStatis, 2020, 3) *level-of-detail-1 (LoD-1) building models*. Here, we rely on the official LoD-1 building model (BKG, 2021) which provides the building ground floors and the height of the building, and (4) data from *publications on the degree of urbanization*. We rely on the data published in the World Urbanization Prospects (UN, 2020).

Based on these raw data, we further process the data to obtain the following indicators: (5) *building structural type.* As discussed above, we assume that multi-family houses (including high-rise buildings, block development, etc.) constitute structurally urban forms of living. Thus, we specify two different classes, namely *urban* and *rural structural building types*. Using the designated function of the buildings based on the official real estate cadaster (ADV, 2008), buildings are differentiated into residential and non-residential buildings in a first step. Buildings in federal states of Germany that do not include a differentiation of the respective functions are classified using a Random Forest approach (Droin, Wurm, & Sulzer, 2020; Wurm, Schmitt, & Taubenböck, 2016). Furthermore, Droin et al. (2020) differentiated the designated residential buildings into four thematic classes (detached, semi-detached and terraced houses are understood as rural and multi-family houses (MFH) are understood as urban, cf. Section 3.1.). We use this classification to derive an (6) *estimation of population numbers*. We disaggregate the population data from the 100 × 100 meter grid onto the available living space in the residential buildings from (5). From the LoD-1 building heights, we calculate the number of floors from building height based on established correlations between the two variables (Wurm et al., 2019; Wurm, Taubenböck, Schardt, Esch, & Dech, 2011). Hence, we derive the living area per building and disaggregate the population proportionally by a linear disaggregation model. With it, we achieve people per residential building.

4. Results

As already mentioned, the story is told that in principle the urbanization process is largely completed in Western countries (e.g. Zukunftsinstitut, 2021). The benchmark for Germany is 80.3% of the population already lives in urban areas and the trend is rising (UN, 2020). In the following, we show variants of such statistics that question these general narratives and we propose a procedure to present these statistics in a more nuanced way.

4.1. The territorial approach

What is classified as *'urban'* is highly heterogeneous between countries. If one applies these multitudes of used thresholds across the globe to the administrative areas of Germany, one obtains very heterogeneous degrees of urbanization indeed. In this range of thresholds, one extreme is 200 inhabitants per municipality (applied in Iceland, Greenland, Australia, Denmark). Applied to Germany means that 99.9% - almost the entire population - would be classified as 'urban' (Fig. 1). The other extremes are, if the Japanese threshold of 50,000 inhabitants per municipality is applied, that only around 41.0% of Germany's population would be considered 'urban'. Angel et al. (2018) even propose 100,000 people or more for the classification of the 'urban' to ensure a focus on cities. In this case, even only 32.1% would be classified 'urban' in Germany. Fig. 1 provides an overview of the quantitative share of the population classified as urban versus rural in a progression diagram using the different national thresholds. It becomes clear that the range between 99.9% and 32.1% is extremely wide.

These applied thresholds and the related variable, of course, have spatial implications on the degrees of urbanization. If we again focus on the extremes, then according to the Icelandic definition, virtually all of Germany is mapped as urban (Fig. 2a). Both, in the context of the conceptual differentiation between *'the urban'* and *'the rural'* in general, as well as in the sense of what we understand as urban, i.e. a dense form of living, this threshold value seems nonsensical for Germany. The threshold applied in Japan (>50,000) or the even more restrictive one of Angel et al. (2018) (>100,000), in turn, identify only large cities and few metropolitan areas such as Berlin, Hamburg, Munich or the Rhein-Ruhr area as urban. Small and medium-sized towns, however, are classified as rural (Fig. 2a). From these extremes, one can conclude that a meaningful threshold must lie somewhere in between. However, there can be no unequivocal true or false. It is evident in the gradations in between, that setting a threshold will always lead to discussions.

To add to these variants, some countries apply not just an absolute threshold, but a second condition for the classification of '*the urban*'. The combination of absolute population numbers with a population density threshold adds to the complexity. Classifying the urban at e.g. 1000 inhabitants and a population density at 400 inhabitants per km^2, as Canada does, makes an immense difference compared to the threshold of 1000. Fig. 2b illustrates the enormous spatial impact. Here, too, it is predominantly the large cities and metropolitan areas that remain.

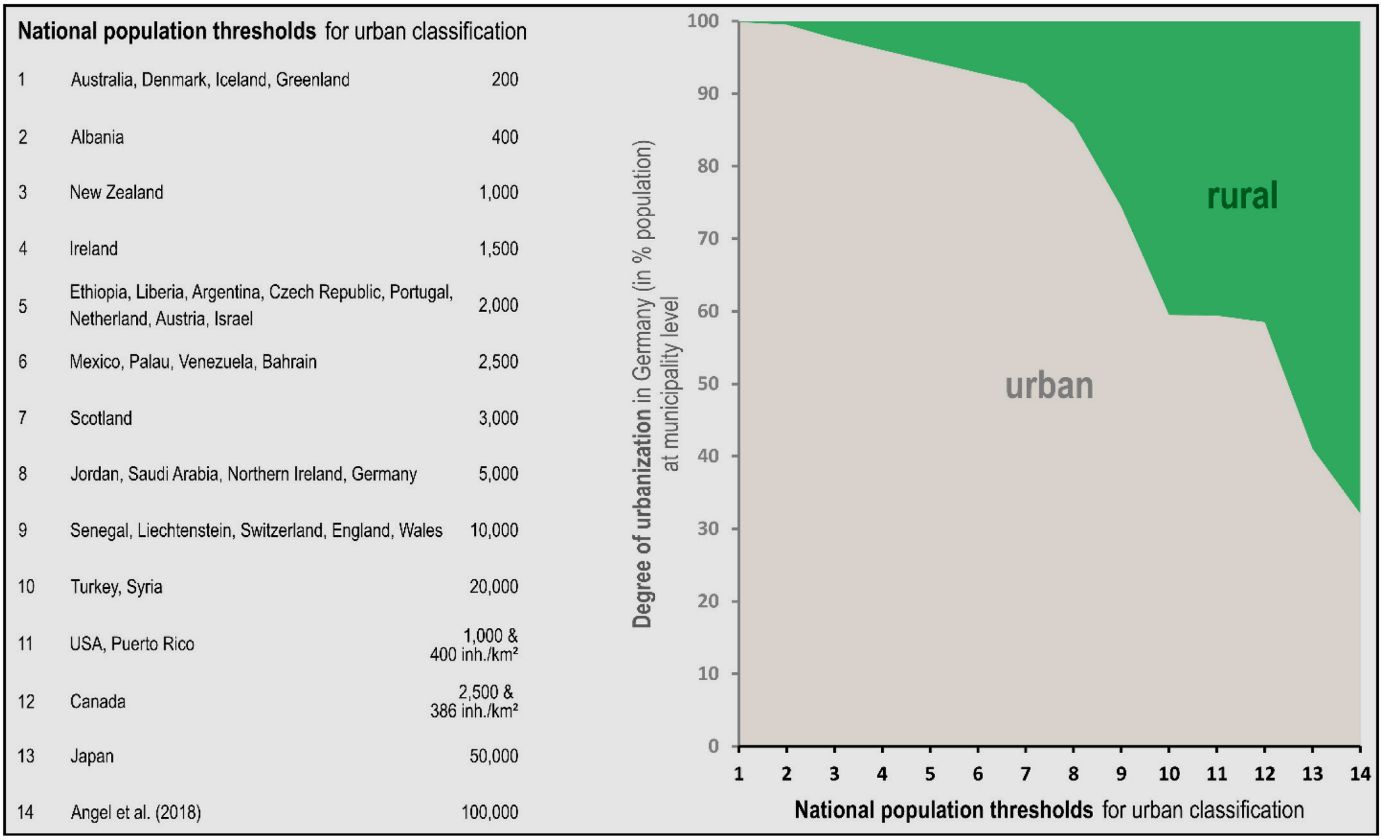

Fig. 1. Degree of urbanization for Germany depending on the population thresholds applied (thresholds as in UN, 2020 as well as from Angel et al., 2018) at administrative units.

4.2. The grid-based approach

For the grid-based approach, we apply three different variables for mapping: the building density, the population density and the share of a certain building type. The mapping results are generally not as continuous as the administrative level apparently; rather, a porous picture of the settlement area emerges (Fig. 2c, d, e). The threshold values illustrated, as examples, also show a very variable, cartographic picture here: From the very low threshold of 5% of building density, which then classifies '*the urban*' widely beyond the area of what is regarded as large, medium and small-sized cities to the threshold of 40% of building density, where even within the metropolises only the centers remain urban. It shows again that almost any image can be created.

If we systematically calculate thresholds for all variables from the minimum to the maximum, all of Germany is classified as 'urban' at the minimum and at the maximum it is classified as completely 'rural'. The course between the extremes shows us the respective degree of urbanization in relation to the particular threshold applied (Fig. 3).

For interpretation purposes, let us compare the results in Fig. 3 with the United Nations benchmark that Germany is 80.3% urbanized: If we use the variable 'building density' to match these 80.3%, we find that this would be the case from a threshold value of 4.7% (see Fig. 3a1). If we reference the urbanization rate of 80.3% to the variable population instead of building density, then this would be the case for a threshold of 11.2% (see Fig. 3a2). And if we use the share to the maximum value of population density in Germany per grid cell, then this would be the case for a threshold of 6.9% (see Fig. 3b). Finally, if we reference the 80.3% degree of urbanization on the share of MFH, this would be the case from a threshold of 1.4% (see Fig. 3c). All of these threshold values derived to achieve the 80.3% degree of urbanization as suggested by the UN (2018) appear to have comparatively low densities, both in terms of the built landscape as well as for population. Studies that deal with suburban structures, i.e. in peri-urban areas that are generally assumed to be of low-density, show densities in the medians that are 15% in the lowest range, but around 20% appears to be much more characteristic (e.g. Taubenböck, Kehrer, & Wurm, 2015). Thus, the built structures that are counted as urban using the 80.3% degree of urbanization do not seem to correspond to what we perceive as urban.

4.3. A probability-based approach for specifying the degree of urbanization in a differentiated way

Which variable for the classification of '*the urban*' versus '*the rural*' is best, which threshold is suitable, which spatial entity makes sense? This cannot be said with any certainty. To nevertheless arrive at a statement of how urbanized Germany is, we propose the combination of all the different conceptual approaches introduced above. In our example, we choose the combination of 29 variants (cf. Section 3.1.). The result is a classification at grid level, which allows a probability-based allocation to 'urban' or 'rural' (Fig. 4). The illustration shows the complexity of the problem in that the graded probabilities are a product of conceptual, parametric, and threshold-based variations.

The suggested three-part classification, i.e. high probability of being '*urban*' or '*rural*', as well as a '*range in between*', allows a differentiated quantification: We can safely say that 1.9% of Germany's land area has a clearly urban land cover. It is remarkable that on this comparatively small area, almost 50% (41.59 million) of the population resides. In other words, Germany is at least 50.0% urbanized. 32% of the area, in turn, is clearly assigned to a rural land cover. However, only 3.95 million people (4.8%) live there. The 66.1% of the land area or the 45.3% (37.65 million) of the population between these clear classifications could of course also be classified dichotomously into urban and rural according to a methodological specification. The probabilities for one of the two classes, however, are not so clear-cut; they represent a kind of transition.

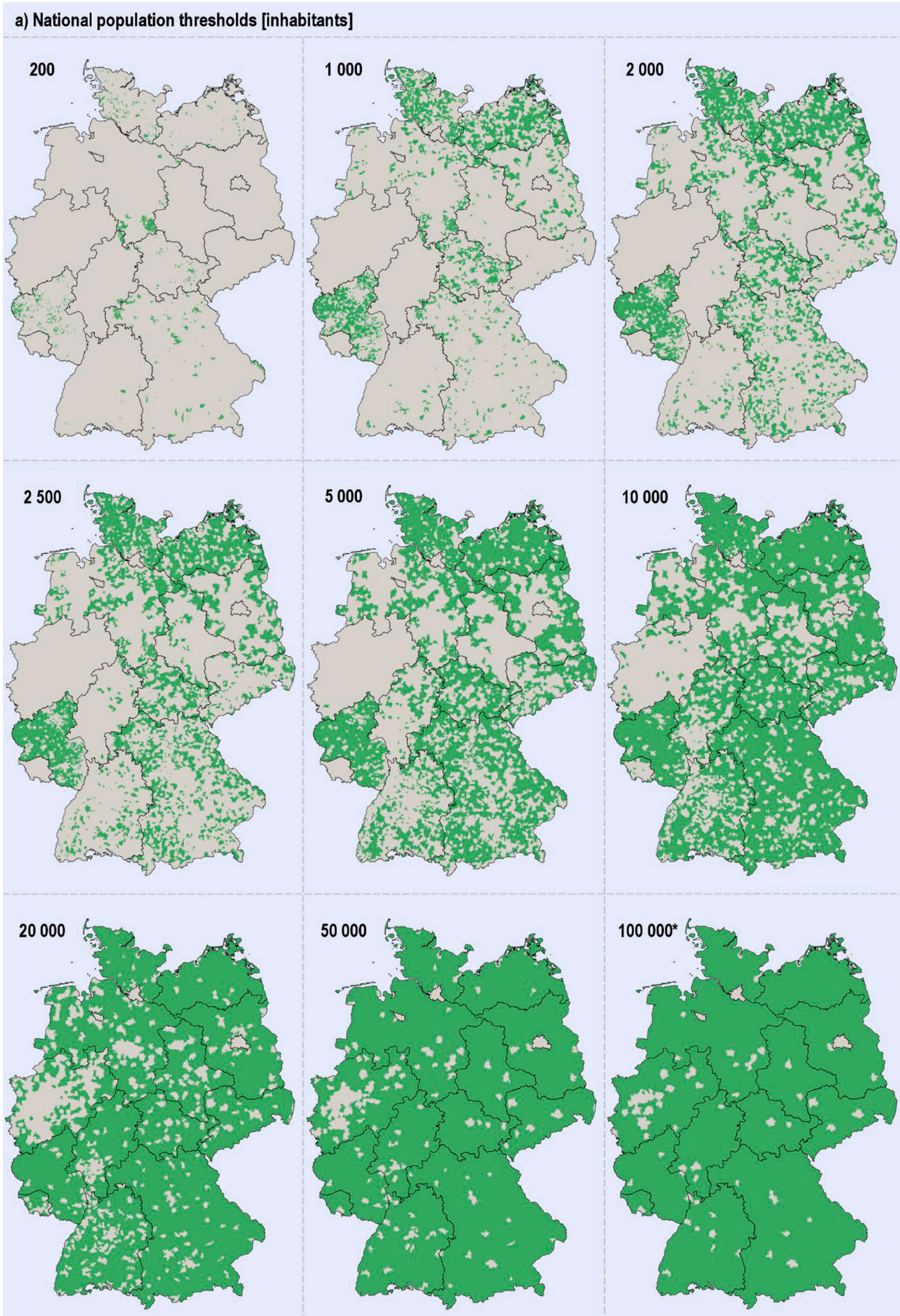

Fig. 2. Degrees of urbanization for Germany: at *administrative units* depending on a) national population single thresholds, and b) on national thresholds combined from absolute population and density (thresholds as in UN, 2020 as well as in Angel et al., 2018); at *grid-level* depending on c) a selected threshold on the share of multi-family homes per grid cell, d) a selection of thresholds on the building density, and e) a selection of thresholds on the population density relative to the measured maximum value of population density in Germany.

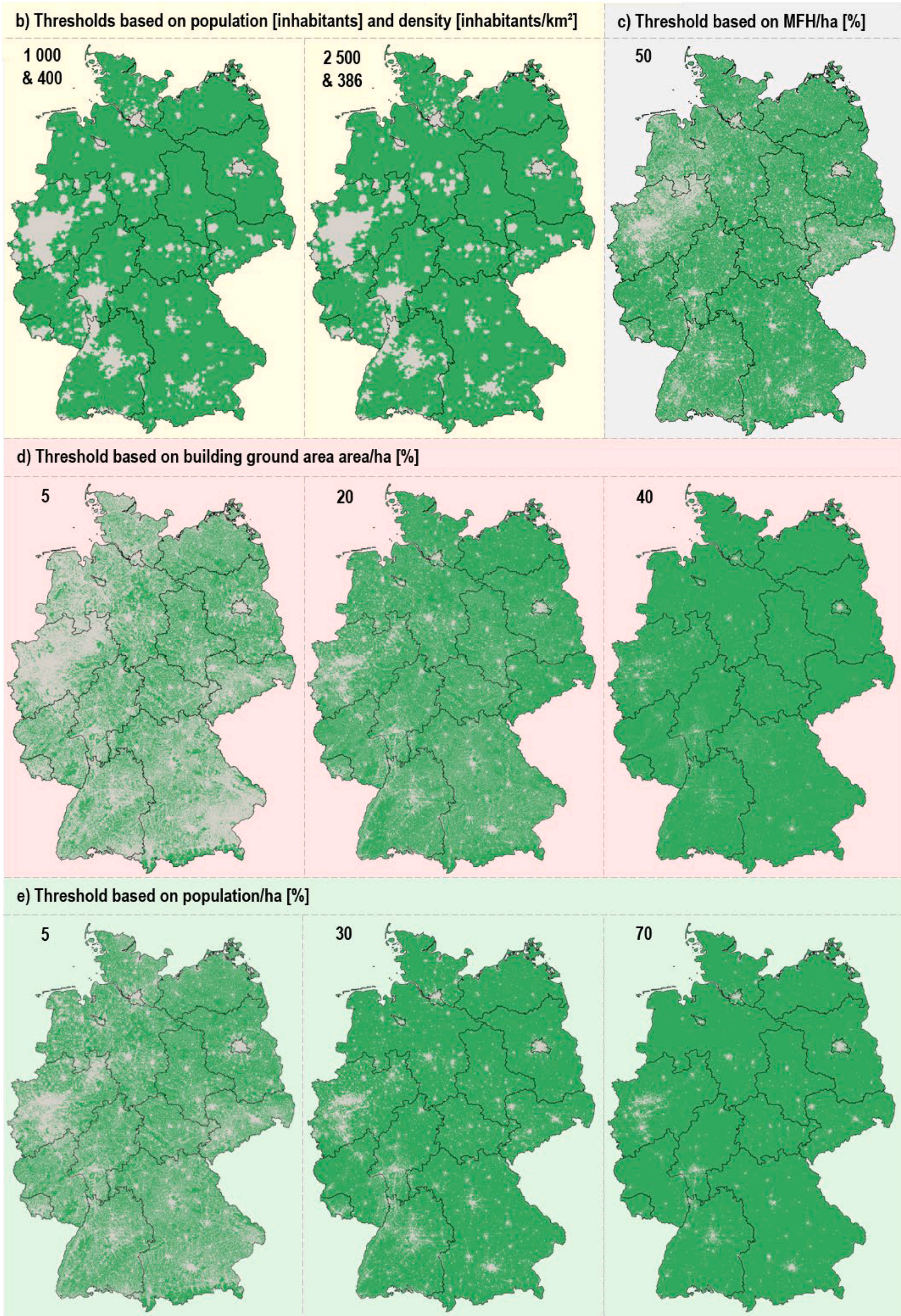

Fig. 2. (*continued*).

To present this transition in a more differentiated way, we have subclassified this range of uncertainty based on quantiles. With it, we count another 18.1% of the population closer to '*the urban*', and 12.6% correspondingly closer to '*the rural*' (Fig. 4).

In other words, in this conceptualization Germany is certainly at least 50.0% urbanized, probably as much as 68.1% of the population.

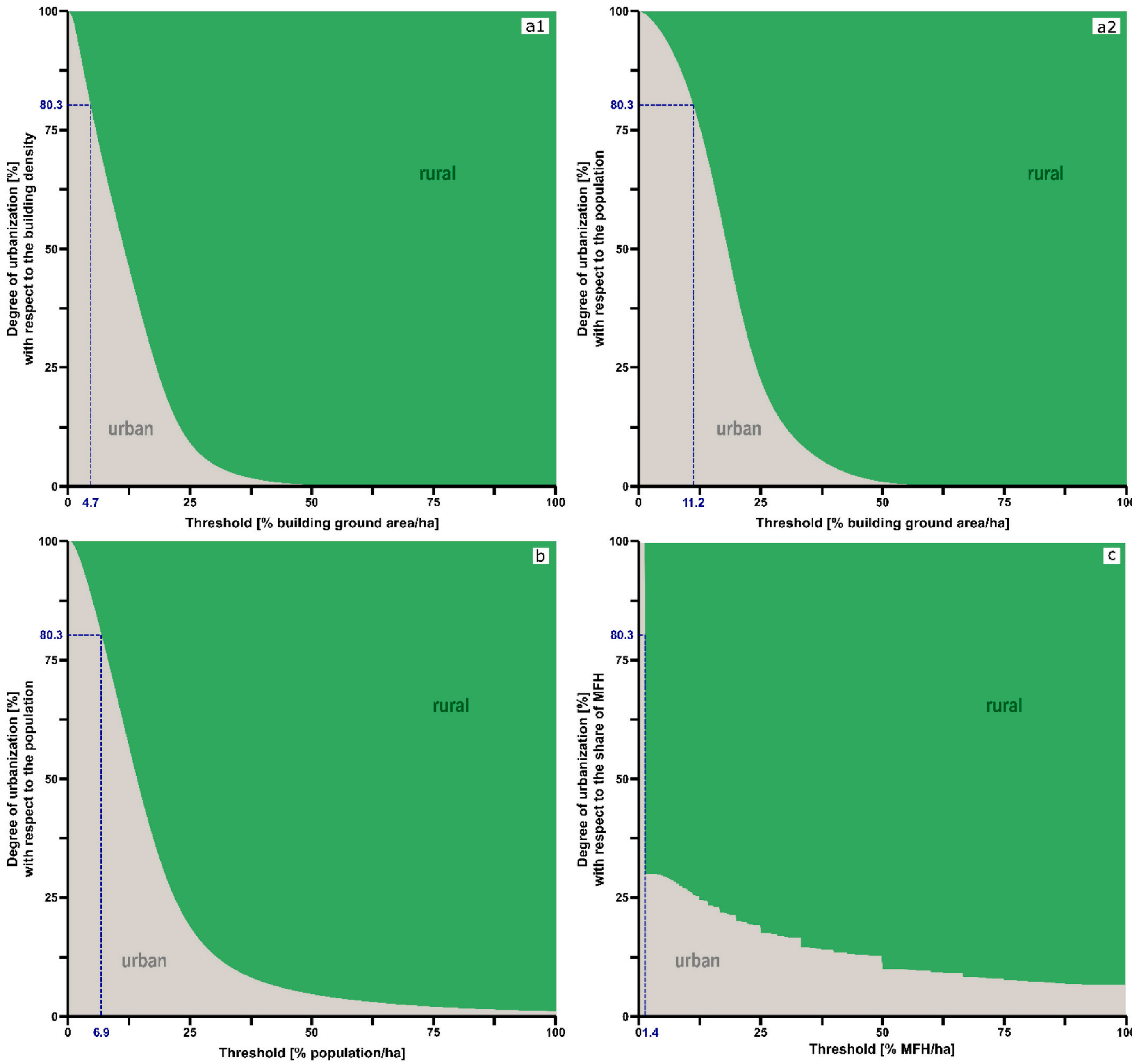

Fig. 3. Degree of urbanization for Germany depending on the thresholds applied at grid level; a1) thresholds for % building ground area/ha with respect to the building density, and a2) with respect to the population; b) thresholds for % population/ha with respect to the population; c) thresholds for % MFH/ha with respect to the share of MFH. The horizontal dotted blue lines indicate the 80.3% degree of urbanization as suggested by the UN (2018). The vertical dotted blue lines indicate the particular threshold to achieve the 80.3% degree of urbanization for Germany. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

And, Germany is certainly rural to at least 4.8% of the population, probably as much as 17.3%. The missing 14.6% feature a high level of uncertainty according to our probability-based approach. We thus do not assign these to a type and these remain in the *"range in between"* class. This type of land cover is sometimes regarded as suburbia, intermediate city (Zwischenstadt) or settlement mash. We believe that this more nuanced, multi-part specification allows for a more differentiated statement about the degree of urbanization.

5. Discussion

"The world is becoming an urban one" has been embraced as meta-narrative by influential thinkers, researchers, practitioners or politicians (Burdett & Sudjic, 2011; Glaeser, 2010; Ash, Jasny, Robert, Stone, & Sugden, 2008; Sennett, 2018; UN, 2018, among many others). This narrative is repeated with monotonous regularity across diverse discursive, scientific, social, economic, environmental, institutional and political terrains (Brenner & Schmid, 2013). The referenced urbanization trend is certainly correct to describe one of the main processes of global change. However, our study shows that this statement is based on an inconsistent conception and that the numbers can easily be misinterpreted or manipulated. So, what does this mean?

First of all, we have to constitute: The figure that 56.6% of the world's population lives in urbanized areas (UN, 2018) arises from the synopsis of national statistics. As a compendium of national realities, it has therefore absolute justification. However, the global figure cites

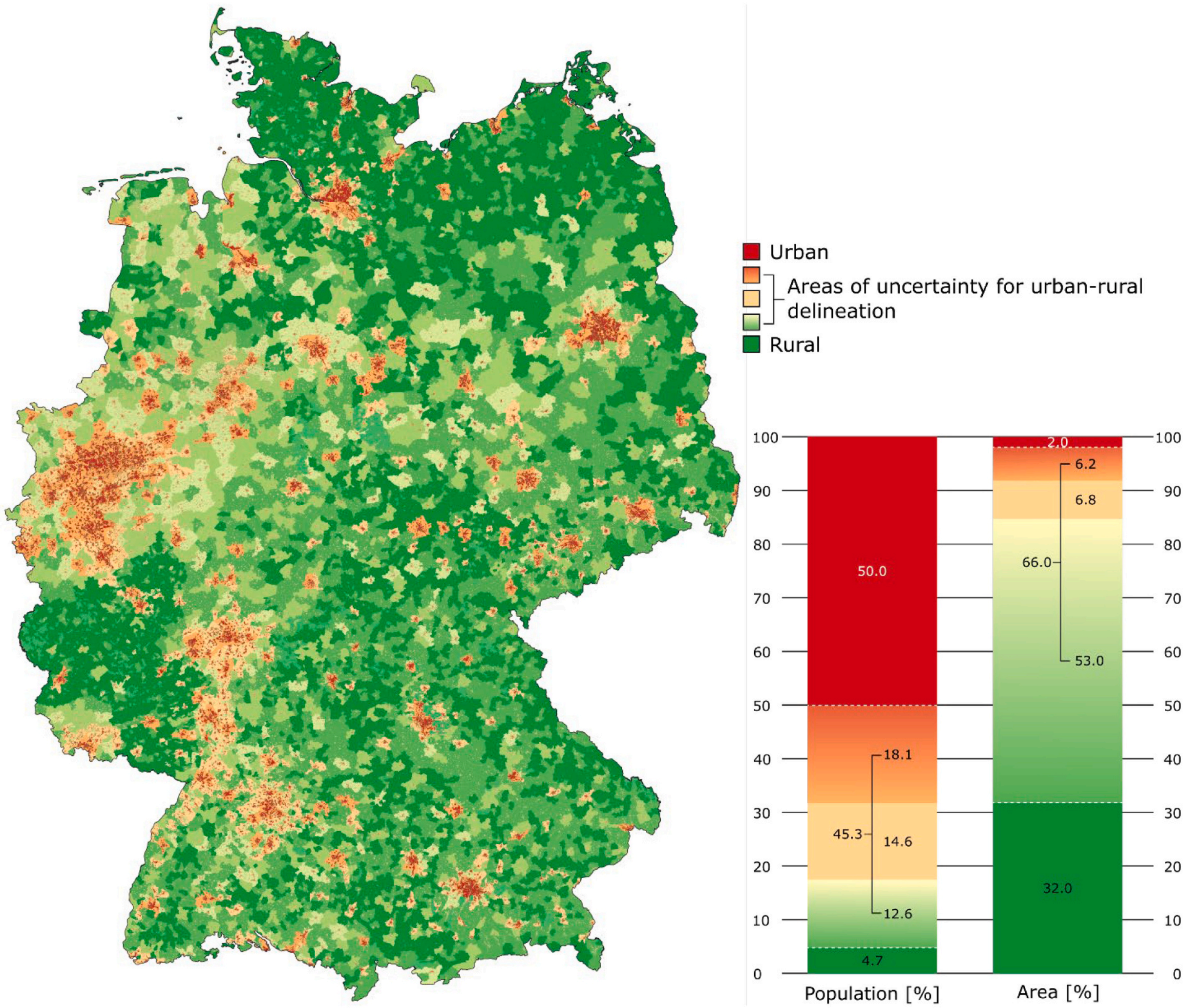

Fig. 4. Degree of urbanization for Germany based on the proposed probability-based approach: Cartographic illustration and statistics on population and area shares.

results from a highly inconsistent approach. In our view, it will only remain valid if the inconsistency of the methodological calculation is clearly stated and the uncertainties are thus expressed. If one projects, as we have done in this study, e.g. the extremes of the thresholds used across the globe to Germany in a consistent manner, the range of results is from 32.1% to 99.9% urbanized. This range shows how fragile the statistic is and it does not really allow any truly justified statement about the degree of urbanization on our planet. Thus, we should always critically question the accepted and often used statistics so that they cannot be reinterpreted depending on the particular direction of any ideological argument. While the trend towards higher population shares in urban areas may certainly be correct, any absolute share given by any study must be viewed with caution. Since facts in the spatial sciences, as shown, contain ambiguities, we tried to ensure (decisional) transparency (Beerbaum & Puaschunder, 2019), and explainability (Benke & Benke, 2018), i.e. we made our conceptual thinking, the specific sources of data used and the ones not used or not available, the applied methods and the interpretation of variable results transparent.

Secondly, it becomes obvious that it is difficult to determine how urbanized our empirical example of Germany de facto is. With a closer look to our results, however, from our point of view, Germany is by far not as 'urban' as commonly assumed. The UN (2020) set the degree of urbanization to 80.3% based on the threshold value 5000 inhabitants per administrative unit. Eurostat (2021) defines the degree of urbanization for Germany at 69.6% using a 1km^2 grid and clusters of neighboring grid cells with a density of at least 300 inhabitants per km^2 and at least 5000 inhabitants. It is clear to us that any specification of methodological approaches and thresholds must lead to opposition. Nevertheless, we would like to make the following arguments here: In our experience, the self-perception of German citizens in places with 5000 or only slightly more inhabitants is by no means an entirely or unambiguously urban one. If we additionally allow for the structural perspective at grid-level, i.e. that urban also means a dense form of living in multi-family buildings, then we even measure much lower figures. And, to achieve e.g. the suggested 80.3% at grid-level, building density values need to be set at 11.2% or even only to 4.7%. These are building densities that are lower than typical densities of areas of single-detached houses which are often located at the transition between urban and rural. We therefore propose a different way of presenting the degree of urbanization: A differentiated representation over a range of uncertainties. By combining different approaches, we can definitely say that 50.0% of the population in Germany is urbanized, 4.8% is rural. The range in between of 45.3% is fraught with uncertainty. But this can be differentiated as well, further 18.1% tend to be closer to '*the urban*', further 12.6% tend to be closer to '*the rural*', and 14.6% feature such a high level of uncertainty that we classify them to the *'range in between'* class. This 'range in between' is a spatial location and empirical description of an urban-rural transition zone, which correspond to conceptual terms such as urban-rural continuum or the urban-rural gradient. The combined, probability-based approach allows us, through the high spatial resolution of the grid-level, to differentiate the degree of urbanization within administrative areas: for example, the probability of being classified 'urban' for a single-family residential area in a metropolitan community is higher than for a comparable single-family residential area in a low-density, village unit. We think that there is more clarity in this complication of the classification. In consequence, we believe from these figures that the degree of urbanization in territorial and structural terms is far from the indicated 80.3% or 69.6%. Thus, we conclude that we are far from the meta-narrative that urbanization is nearly complete in Germany. It is obvious that a higher proportion of the degree of urbanization should be in line with efficient land use, less land consumption and higher degrees of settlement density. However, it remains to be remembered, that this statement of lower degrees of densities in spatio-quantitative numbers could also be calculated with other variants which might change the numbers. And, this particular approach does not necessarily apply to an urban lifestyle which possibly make up higher proportions of the population.

This latter argument leads us, *thirdly,* based on the data available and applied here, to the remark that our approach is reduced to the variables building density, population density, and the share of certain building types. The 'urban' does also have other manifestations: The indicated urban lifestyle, which increasingly applies not only to city dwellers but is becoming the model of lifestyle in general, is not considered in our study. It manifests itself by a porous spatial form that applies more to people than to territorial forms of society. It is the formation of different spatial logics that produce their own logic of socialization through density in space (Held, 2005). Multi-criteria approaches using physical, demographic as well as socio-economic variables try to take that into account (e.g. Küpper, 2016). The data specifically for such multi-criteria approaches beyond physical and demographic domains, however, are unavailable at the very high spatial grid-resolution applied in our study and therefore cannot be integrated here. It is perfectly clear to us that our assumptions are abstracting reality: single-family homes, as example, framed by dense, urban block developments may have to do more with the urban (life) than isolated block developments in a rural, village setting. We account for this by showing what different shares of MFHs mean with respect to being classified as 'urban' or 'rural' by systematically testing thresholds over the fraction of MFHs at grid level. In our combined, probability-based approach, we apply a distribution of thresholds of 1, 25, 50,75 and 99% along the entire range, i.e. we consider that there can be no clear right or wrong for the classification. This approach, for all its systematic nature, is of course only one conceptual approach among many possible ones. It is the attempt to combine the most diverse conceptual approaches as the categorization into urban versus rural remains a socially constituting feature. Thus, we think the spatial-quantitative delimitation of these categories, as done in our study, remains necessary: it combines several perspectives and thus approaches the topic in a more multi-faceted way than with one or two variables, but it is clear that it is not a holistic perspective.

Fourthly, our input data is comprehensive, largely consistent and features, compared to data sets in other large area studies on the degree of urbanization, spatially and thematically unprecedented resolutions. And, since the data sets come from official databases, we are convinced that the errors are comparatively small and our result is generally reliable. Nevertheless, they contain errors, in completeness, in consistency, in accuracy. We cannot quantify this error here due to the lack of better data sets, and thus the impact on our analyses cannot be quantified.

Fifth, there is now a need for a consistent approach beyond our sample of Germany to be able to determine the degree of urbanization better and make it more comparable. However, geodata on the individual building level comparable to our cadastral data are not available globally. And yet, there are high resolution and even freely available cadastral building data, e.g. in France (IGN, 2022), the Netherlands (PDOK, 2022) or Luxembourg (Le Governement du Grand-Duché de Luxembourg, 2022). Other data sets from remote sensing or community-based approaches such as Open Street Map (OSM) are also possible input data at the individual building level: Remote sensing-based continental building data, e.g. for Africa (Sirko et al., 2021), South America and Australia (Microsoft, 2022), and national building data for the US, Canada, Uganda, Tanzania, Nigeria, Kenya (Microsoft, 2022) have been derived; however, yet with lower accuracies than cadastral data. OSM data with complete and accurate building footprint coverage exist especially in urbanized areas; however, country-wide coverage is often not given (as e.g. researched by Salvucci and Salvati (2022) for Italy). At the global level, more and more geodata on settlement areas (especially from earth observation, e.g. the Global Urban Footprint (Esch et al., 2012), the Global Human Settlement Layer (Pesaresi et al., 2013), or the Global Impervious Surface Area (GISA) (Huang et al., 2021), among others, become available. For global studies, we still have to make compromises in terms of spatial and thematic resolution – one reason why we have focused on Germany only for this study to experiment with the spatially and thematically unprecedented resolutions. A promising approach without the need for high resolution geospatial data on building footprints or settlement areas is machine learning. The probabilities for being urban, as classified in our study for Germany, can serve as a training dataset. The capabilities applying such classifiers on area-wide remote sensing input data have yet to be systematically explored. We are fully aware that there cannot be one and best method or threshold. We even believe that the systematic test of thresholds and the elaboration of a probability-based range, as we have done for Germany, is needed to be able to grasp the status quo more clearly. By this example, we are more concerned with reigniting the discourse. The point is that we want to make clear: we must not accept the widely unquestioned meta-narrative as the only truth per se. We want to call for constantly questioning ourselves about concepts, data, methods and perspectives. Here we plead for approaches that are more interdisciplinary and pragmatic, i.e. what constitutes the 'urban' has to be illuminated by demographers, geographers, spatial scientists as well as by sociologists, economists, psychologists or lawyers, among others. In order to then generate consistent approaches, one must pragmatically fall back anyway on existing, accurate, area-wide data sets. In this field of tension, it is worth getting closer to the truth.

And *sixth and last*, the places of life, *'the urban*' vs. *'the rural*' are sometimes ideologically, sometimes emotionally charged. A factual discourse, a social, ecological, economic, demographic, or political discussion of direction, must make room for a more differentiated approach. This study attempts to do just that, to put the status quo on the topic of the degree of urbanization on better, more differentiated empirical facts. It has been shown that urban and rural life have highly different implications: Higher density, for instance, is resource-saving (e.g. Bettencourt, 2007), it increases creativity and productivity (e.g. Glaeser, 2010), among many other effects. At the same time, this is offset by higher exposures to air (e.g. Müller, Erbertseder, & Taubenböck, 2022) or noise pollution (Staab, Schady, Weigand, Lakes, & Taubenböck, 2021), by higher living costs, among other effects. Only both, the reliable knowledge of the effects, and the reliable knowledge of how the distribution actually is, allow a discourse. In this paper, we tackled the latter for better empirical evidence in the hope to benefit policy-makers on the global and national levels working on agendas.

6. Conclusion

It can be frustrating to answer the guiding question of this paper *'how urbanized is Germany?'*, with *'it depends'* in the conclusion. It depends on the concept, the data, the spatial units of measurement, the variables or the thresholds applied. In consequence, we conclude that there is a lack of that one and best concept, set of data or methods and just accept that it does not exist. Here, we proposed that the combination of different approaches resulting in a probability-based range of the degree of urbanization providing uncertainties seems to fit the question better. We suggest that further research is needed that could complement this method with other appropriate approaches. Therefore, we advocate reconsidering simple and often superficial dichotomous classifications and we propose in this contribution a more differentiated way of specifying the degree of urbanization.

We believe based on our empirical set-up that Germany's degree of urbanization is between certainly 50.0% up to possibly 68.1% of the population. We must allow this ambiguity, we must allow more narratives instead of the intended single truth, because in spatial science, rarely anything is unambiguous. Nevertheless, this means that the degree of urbanization in Germany is, in our estimation, lower than presented by other statistics.

While this is a clear result, we believe that still more and different concepts, data and methods from various disciplines are needed – concurrently and side by side. This corresponds to the call of Acuto, Parnell, and Seto (2018) that bringing together scholars from disparate fields and reorganizing existing knowledge domains for a transformation of current science – policy interfaces is in demand for a better understanding of '*the urban*'. For the comparably data-rich situation in Germany, as applied in this study, a complement to the applied physical approaches on building density and types and to the population density would be, e.g., data on lifestyles, behavior pattern or attitudes; at the global level, physical or population related approaches cannot rely on such high-resolution data and accuracies yet, and much less so in socioeconomic or other data. Here this presented approach needs to be adapted to the data circumstances. We suggest that it takes both, more different approaches based on other and different data as well as the systematic tests of thresholds to draw a more reliable, more holistic picture of the degree of urbanization. The different results, when viewed together, as we have done here for Germany, promise a clearer, more differentiated picture of the degree of urbanization, without concealing statistical ambiguity. The acceptance that the world is more complex than mathematical correct results is the basis for this. And, the acceptance of lower urbanization degrees than commonly used, demands for a re-consideration of political argumentation, policy development and re-doing empirical research on different implications of '*the urban*' vs. '*the rural*'.

We believe the extension of these multiple approaches to a multidimensional perspective or to larger areas, even the whole world, is necessary to really test the meta-narratives. From our perspective, the German meta-narrative needs to be adapted, and we would not be surprised if it were similar for the entire world.

Acknowledgements

This work is funded by the German Federal Ministry of the Interior and Community under the project "*Fe4ErsiGG_IF-Bund - Fernerkundung für die Ermittlung siedlungsstruktureller Grenzen und Gebietseinheiten*".

References

Acuto, M., Parnell, S., & Seto, K. (2018). Building a global urban science. *Nature Sustainability, 1*, 2–4. https://doi.org/10.1038/s41893-017-0013-9

AdV – Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland. (2008). Dokumentation zur Modellierung der Geoinformationen des amtlichen Vermessungswesens (GeoInfoDok). http://www.adv-online.de/GeoInfoDok/binarywriterservlet?imgUid=c9e63fd2-1153-911a-3b21-718a438ad1b2&uBasVariant=11111111-1111-1111-1111-111111111111&isDownload=true.

Angel, S., Lamson-Hall, P., Galarza, N., & Blei, A. (2018). Our Not-So-Urban World. https://marroninstitute.nyu.edu/papers/our-not-so-urban-world.

Ash, C., Jasny, B., Robert, L., Stone, R., & Sugden, A. (2008). Reimagining cities. *Science, 319*(5864), 739.

Balk, D., Leyk, S., Jones, B., Montgomery, M. R., & Clark, A. (2018). Understanding urbanization: A study of census and satellite-derived urban classes in the United States, 1990-2010. *PLoS One, 13*(12), Article e0208487.

Bartosiewicz, B., & Marcińczak, S. (2020). Investigating polycentric urban regions: Different measures–different results. *Cities, 105*. https://doi.org/10.1016/j.cities.2020.102855

Batty, M., Besussi, E., Maat, K., & Harts, J. J. (2004). Representing multifunctional cities: Density and diversity in space and time. *Built Environment, 30*(4), 324–337. https://doi.org/10.2148/benv.30.4.324.57156

Beerbaum, D., & Puaschunder, J. M. (2019). *A behavioral economics approach to digitalization: The case of a principles-based taxonomy* (pp. 107–122). Emerging Research and Opportunities (IGI Global): Intergenerational Governance and Leadership in the Corporate World.

Benke, K., & Benke, G. (2018). Artificial intelligence and big data in public health. *International Journal of Environmental Research and Public Health, 15*(12), 2796.

Berking, H. (2008). *Städte lassen such an ihrem Gang erkennen wie Menschen. Skizzen zur Erforschung der Stadt und der Städte. In: Berking H & Löw M (Eds): Eigenlogik der Städte*. Frankfurt am Main/New York: Campus.

Bettencourt, L. M. A. (2007). The origins of scaling in cities. *Science, 340*, 1438–1441.

Bocquier, P. (2004). *World Urbanization Prospects: an alternative to the UN model of projection compatible with urban transition theory. No. DIAL Working Paper DT/2004/08*.

Brenner, N., & Schmid, C. (2013). The 'Urban Age' in Question. *International Journal of Urban and Regional Research*, 20–21. http://www.urbantheorylab.net/site/assets/files/1014/brenner_and_schmid_ijurr.pdf.

Budde, R., & Neumann, U. (2018). The size ranking of cities in Germany: Caught by a MAUP? *GeoJournal, 84*, 1447–1464.

Buettner, T. (2014). Urban estimates and projections at the United Nations: The strengths, weaknesses, and underpinnings of the world urbanization prospects. *Spatial Demography, 2*(2), 1–16.

Bundesamt für Kartographie und Geodäsie (BKG). (2021). Dokumentation 3D Gebäudemodell Deutschland - LoD1. https://sg.geodatenzentrum.de/web_public/gdz/dokumentation/deu/LoD1-DE.pdf.

Bundesamt für Kartographie und Geodäsie (BKG) / GeoBasis-DE. (2020). Verwaltungsgebiete 1:250 000. VG250 und VG250-EW. https://gdz.bkg.bund.de/index.php/default/catalog/product/view/id/789/s/verwaltungsgebiete-1-250-000-ebenen-stand-31-12-vg250-ebenen-31-12/category/8/?__store=default. Retrieved, 01.10.2020.

Burdett, R., & Sudjic, D. (2011). Living in the endless city. *Phaidon*, 512.

Castells, M. (1996). *The rise of the network society*. Cambridge/Oxford: Balckwell.

Champion, T., & Hugo, G. (2004). *New forms of urbanization: Beyond the urban-rural dichotomy*. Ashgate Publishing Ltd.

DeStatis. (2020). https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html?nn=3065474.

Dorélien, A., Balk, D., & Todd, M. (2013). What is urban? Comparing a satellite view with the demographic and health surveys. *Population and Development Review, 39*(3), 413–439.

Droin, A., Wurm, M., & Sulzer, W. (2020). *Semantic labelling of building types* (p. 29). Wissenschaftlich-technische Jahrestagung der DGPF, Band: A comparison of two approaches using Random Forest and Deep Learning.

Esch, T., Taubenböck, H., Roth, A., Heldens, W., Felbier, A., Thiel, M., … Dech, S. (2012). TanDEM-X mission—New perspectives for the inventory and monitoring of global settlement patterns. *Journal of Applied Remote Sensing, 6*, 1–21.

Eurostat. (2021). *Applying the degree of urbanisation. ISBN 978-92-76-20306-3*. https://doi.org/10.2785/706535

Florida, R., Gulden, T., & Mellander, C. (2008). The rise of the mega-region. *Cambridge Journal of Regions, Economy and Society, 1*, 459–476.

Glaeser, E. (2010). *Triumph of the city* (p. 352). London: Penguin Press HC.

Held, G. (2005). *Territorium und Großstadt. Die räumliche Differenzierung der Moderne*. Wiesbaden: VS Verlag für Sozialwissenschaften.

Huang, X., Li, J., Yang, J., Zhang, Z., Li, D., & Liu, D. (2021). 30 m global impervious surface area dynamics and urban expansion pattern observed by Landsat satellites: From 1972 to 2019. *Science China Earth Sciences*. https://doi.org/10.1007/s11430-020-9797-9

Institut National de l''information géographique et forestiére (IGN). (2022). BD TOPO®. Version 3.0. Descriptif du contenu. https://geoservices.ign.fr/sites/default/files/2022-04/DC_BDTOPO_3-0.pdf.

Joint Research Center (JRC). (2021). GHS-SMOD R2019A. https://ghsl.jrc.ec.europa.eu/ghs_smod2019.php (accessed 10.01.2022).

Kim, J. I., Yeo, C. H., & Kwon, J. (2014). Spatial change in urban employment distribution in Seoul metropolitan city: Clustering, dispersion and general dispersion. *International Journal of Urban Sciences, 18*, 355–372.

Krehl, A. (2016). Urban subcentres in German city regions: Identification, understanding, comparison. In *Papers in Regional Science online first*. https://doi.org/10.1111/pirs.12235

Küpper, P. (2016). *Abgrenzung und Typisierung ländlicher Räume*. Braunschweig: Thünen-Institut, Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei. https://doi.org/10.3220/WP1481532921000

Le Governement du Grand-Duché de Luxembourg. (2022). Bâtiments 3D (LOD1 – Level of Detail 1). https://data.public.lu/en/datasets/5cecd25a4384b06ad27e5c58/#_.

Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecology, 2014*(29), 763–771.

López-Goyburua, P., & García-Montero, L. G. (2018). The urban-rural interface as an area with characteristics of its own in urban planning: A review sustainable cities and society. *43*(November 2018), 157–165.

Löw, M. (2008). *Soziologie der Städte*. Frankfurt am Main: Suhrkamp.

Malizia, N. (2013). The effect of data inaccuracy on tests of space-time interaction. *Transactions in GIS, 17*(3), 426–451.

Melchiori, M., Florczyk, A. F., Freire, S., Schiavina, M., Pesaresi, M., & Kemper, T. (2018). Unveiling 25 years of planetary urbanization with remote sensing: perspectives from the global human settlement layer. *Remote Sensing, 10*(5). https://www.mdpi.com/2072-4292/10/5/768.

Microsoft. (2022). https://www.microsoft.com/en-us/maps/building-footprints (accessed: 05/2022).

Müller, I., Erbertseder, T., & Taubenböck, H. (2022). Tropospheric NO2: explorative analyses of spatial variability and impact factors. *Remote Sensing of Environment, 270*, Article 112839.

Nassehi, A. (2002). Dichte Räume. Stadt als Synchronisations- und Inklusionsmaschinen. In M. Löw (Ed.), *Differenzierung des Städtischen* (pp. 211–232). Opladen: Leske + Budrich.
National Academies of Sciences, Engineering, and Medicine. (2016). *Rationalizing Rural Area Classifications for the Economic Research Service: A Workshop Summary*. National Academies Press.
Openshaw, S. (1983). *The modifiable areal unit problem*. Norwick [Norfolk]: Geo Books.
Pahl, R. E. (1966). The rural-urban continuum. *Journal of the European Society of Rural Sociology., 6*(3), 299–329. https://doi.org/10.1111/j.1467-9523.1966.tb00537.x
PDOK. (2022). 3D Basisvoorziening. https://3d.kadaster.nl/basisvoorziening-3d/.
Pesaresi, M., Huadong, G., Blaes, X., Ehrlich, D., Ferri, S., Gueguen, L., & Zanchetta, L. (2013). A global human settlement layer from optical HR/VHR RS data: Concept and first results. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 6*(6), 2102–2131.
Redepenning, M., & Hefner, C. (2018). Stadt und Land als Klassiker der Raumwissenschaften. In A. Hlukhovych (Ed.), *Kultur und kulturelle Bildung: Interdisziplinäre Verortungen – Lehrerinnen- und Lehrerbildung – Perspektiven für die Schule, Bamberg 2018* (pp. 77–103).
Roca Cladera, J., Marmolejo Duarte, C. R., & Moix, M. (2009). Urban structure and polycentrism: Towards a redefinition of the sub-Centre concept. *Urban Studies, 46*, 2841–2868.
Salvucci, G., & Salvati, L. (2022). Official statistics, building censuses, and OpenStreetMap completeness in Italy. *ISPRS International Journal of Geoinformation, 11*(29). doi:10.3390/ijgi11010029.
Schabenberger, O., & Gotway, C. A. (2005). *Statistical methods for spatial data analysis*. Taylor & Francis.
Sennett, R. (2018). *Building and Dwelling: Ethics for the City. Allen Lane* (1st ed.) 368 pages.
Shearmur, R. (2017). Urban bias in innovation studies. In H. Bathelt, P. Cohendet, S. Henn, & L. Simon (Eds.), *The Elgar Companion to Innovation and Knowledge Creation* (pp. 440–456). https://doi.org/10.4337/9781782548522.00037
Sievers, T. (1997). *Zwischenstadt: zwischen Ort und Welt, Raum und Zeit, Stadt und Land*. Braunschweig/Wiesbaden: Verlag Friedrich Viehweg & Sohn.
Sirko, W., Kashubin, S., Ritter, M., Annkah, A., Bouchareb, Y. S. E., Dauphin, Y., Keysers, D., Neumann, M., Cisse, M., & Quinn, J. *Continental-Scale building detection from High Resolution Satellite Imagery*. (2021). https://arxiv.org/abs/2107.12283v2.
Socio-economic Data and Applications Center (SEDAC). (2021). *Global Rural-Urban Mapping Project (GRUMP). v1*. https://sedac.ciesin.columbia.edu/data/collection/grump-v1/methods (accessed, 30.08.2021).
Staab, J., Schady, A., Weigand, M., Lakes, T., & Taubenböck, H. (2021). Predicting traffic noise using land use regression – A scalable approach. *Journal of Exposure Science & Environmental Epidemiology*. https://doi.org/10.1038/s41370-021-00355-z
Taubenböck, H., Kehrer, J., & Wurm, M. (2015). *Zu Stein gewordene Philosophien – Die Morphologie geplanter Wohnviertel. SpringerSpektrum. S* (pp. 135–147).
Taubenböck, H., Standfuß, I., Klotz, M., & Wurm, M. (2016). The physical density of the city – Deconstruction of the delusive density measure with evidence from two European megacities. *ISPRS Internatl. Journal of Geo-Information, 5*(11), 1–24.
Taubenböck, H., Standfuß, I., Wurm, M., Krehl, A., & Siedentop, S. (2017). Measuring morphologic polycentricity – A comparative analysis of urban mass concentrations using remote sensing data. *Computers, Environment and Urban Systems, 64*, 42–56.
Taubenböck, H., Weigand, M., Esch, T., Staab, J., Wurm, M., Mast, J., & Dech, S. (2019). A new ranking of the world's largest cities - do administrative units obscure morphological realities? *Remote Sensing of Environment, 232*.
du Toit Marié, J., & Cilliers, S. S. (2011). Aspects influencing the selection of representative urbanization measures to quantify urban–rural gradients. *Landscape Ecology, 26*. pages169–181 (2011).
Tonkiss, F. (2013). *Cities by design: The social life of urban form*. Cambridge, UK: Polity.
United Nations, Department of Economic and Social Affairs, Population Division. (2018). 2018 Revision of the World Urbanization Prospects. https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html.
United Nations, Department of Economic and Social Affairs, Population Division. (2020). Demographic Yearbook, 70th issue. https://unstats.un.org/unsd/demographic-social/products/dyb/dybsets/2019.pdf.
Wirth, L. (1969). Urbanism as a way of life. In R. Sennett (Ed.), *Classic essays on the culture of cities, Prentice Hall*. NJ: Englewood Cliffs [1937].
Wurm, M., Goebel, J., Wagner, G. G., Weigand, M., Dech, S., & Taubenböck, H. (2019). *Inferring floor area ratio thresholds for the delineation of city centers based on cognitive perception*. Environ, Plan: B Urban Anal. City Sci.
Wurm, M., Schmitt, A., & Taubenböck, H. (2016). Building types classification using shape-based features and linear discriminant functions. *IEEE Journal of Selected Topics in Applied Earth Observation & Remote Sensing., 9*(5), 1901–1912.
Wurm, M., Taubenböck, H., Schardt, M., Esch, T., & Dech, S. (2011). Object-based image information fusion using multisensor earth observation data over urban areas. *International Journal of Image and Data Fusion, 2*, 121–147.
Zukunftsinstitut. (2021). Die Stadt von morgen. https://www.zukunftsinstitut.de/artikel/urbanisierung-die-stadt-von-morgen/. retrieved. 12.01.2022.