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Urban Patterns from Space: A Remote Sensing Based Comparison Between France and Germany

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Abstract

This article presents two novel methods on how to derive and visualise settlement patterns from space: a non-parametric approach called multi-scale homogeneity and a parametric, unsupervised approach known as hierarchical multi-scale clustering that models the urban clusters with the help of Gaussian bell curves. The main advantage of remote sensing based acquisition and fully automated evaluation methods is their consistency over large coverages. The Global Urban Footprint-Density (GUF-DenS) indicating the degree of impervious surfaces worldwide serves as database. The geographical focus lies on the neighbouring central-European countries France and Germany. Assuming that the centralist and federal administrative systems resulting from the individual history show a certain impact on the urban patterns, both countries are first examined separately, then together as union. The numerical comparison proofs the expected differences: the settlement pattern of the capital Paris as the largest metropolitan region in France is dominating, whereas several economic clusters of more of less similar size like Rhine–Ruhr and Rhine–Main characterise the German urban landscape. The most interesting and unexpected findings are located along the border, where neighbouring urban ellipses overlay in the separate processing and form transnational clusters when processed as union. One can interpret that the national border does not play a role in the urban development (any longer). The temporal change of the settlement patterns as effect of the regional planning strategies or the opening of the inner-European border cannot be derived from the mono-temporal GUF-DenS and thus, will be subject to future studies.

Keywords Settlement pattern · Built-up density · Spatial homogeneity · Unsupervised clustering · Cluster analysis · Gaussian mixture model · Inner-European border

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Städtische Strukturen aus dem All: ein Vergleich zwischen Frankreich und Deutschland auf Basis von Satellitenaufnahmen

Kurzfassung

In diesem Artikel werden zwei neuentwickelte Methoden zur Ableitung und Visualisierung von Siedlungsmustern aus Satellitenaufnahmen vorgestellt: ein nicht-parametrischer Ansatz (multi-scale homogeneity) und ein parametrischer, unüberwachter Ansatz (hierarchical multi-scale clustering), welcher die urbanen Zentren mit Hilfe von Gaußschen Glockenkurven modelliert. Der große Vorteil von fernerkundungsbasierten Erfassungs- und vollautomatischen Auswerteverfahren ist ihre Konsistenz über große Abdeckungen. Die verwendeten Daten stammen aus dem Global Urban Footprint - Density (GUF-DenS), der den Grad der Versiegelung weltweit angibt. Geografisch bezieht sich die Studie auf die mitteleuropäischen Nachbarländer Frankreich und Deutschland. Unter der Annahme, dass die aus der jeweiligen Geschichte resultierenden zentralistischen und föderalen Verwaltungssysteme einen gewissen Einfluss auf die urbanen Muster zeigen, werden beide Länder zunächst getrennt, dann gemeinsam als eine Einheit untersucht. Der numerische Vergleich belegt die erwarteten Unterschiede: Die Hauptstadt Paris ist nach wie vor die mit Abstand größte Metropolregion Frankreichs, während in Deutschland mehrere mehr oder weniger ähnlich große Wirtschaftszentren wie Rhine-Ruhr und Rhine-Main die Stadtlandschaft prägen. Die interessantesten und auch unerwarteten Ergebnisse reihen sich entlang der Grenze auf, wo benachbarte Stadtellipsen beider Länder sich in der getrennten Betrachtung überlagern und transnationale Stadtcluster bilden, wenn man die Länder als Einheit betrachtet. Daraus kann man schließen, dass die Landesgrenze keine Rolle (mehr) in der Stadtentwicklung spielt. Die zeitliche Veränderung der Siedlungsmuster als Auswirkung der Raumordnungspolitik oder auch der Öffnung der innereuropäischen Grenze kann aus dem mono-temporalen GUF-DenS nicht abgelesen werden und wird daher im Fokus zukünftiger Forschungen stehen.

1 Introduction

Three wars in only 75 years—beginning with the Franco-Prussian War (1870–1871) over World War I (1914–1918) until World War II (1939–1945)—established a French–German enmity in the first half of the twentieth century (Daniel et al. 2004). In this time, France could look back to a long traditional kingdom starting in medieval times (Price 2014). On the contrary, Germany was a confederation of numerous small principalities under the lead of Prussia newly established after the Franco-Prussian War (Duggan et al. 2014). Hence, two neighbouring countries evolved out of a completely different history that resulted in two different administrative systems: centralist in France (Loughlin 2007) vs. federal in Germany (Umbach 2002). Due to their enmity back in these times, the activities along the common border have been restricted to isolation and defense for many decades (Hoepel 2014) , which is expressed (e.g.) in the Maginot Line and the West Wall.

The relation between both countries changed to the opposite in the second half of the twentieth century. The European Coal and Steel Community established in 1951 united six European countries, amongst them Germany and France (Duggan et al. 2023). The Elysée Treaty of friendship from 1963 between France and Germany foresees regular appointments and a close cooperation (i.a.) regarding defense, education and youth (France Diplomacy 2023). With the Schengen Agreement of 1985, the national borders were opened, i.e. trespassing without border control has been possible from this time on European Commission (2023). France and Germany became the driving forces in the European-wide unification process that culminated in the European Union (EU) in 1993 (European Union 2023). Within the EU, some partners even agreed to the economic and monetary union which means that the national currency was replaced by the common European currency EURO in the year 1999 as accounting currency and in 2002 cash respectively, which simplified transnational economic relations and travel (European Commission 1997). Several other countries within the European Union joined the Euro zone later on.

From today's perspective, the French–German friendship can be categorised as success story of peaceful cooperation between neighbouring countries and as indispensable motor of the European unification (European Council 2015; Poptcheva 2015; Franke and Puglierin 2020). Germany with 82,7 million inhabitants on 357,588 km^2 (231 people per km^2) and (metropolitan) France with 66.2 million inhabitants on 543,940 km^2 (122 people per km^2) together account for 21% of the area, 33% of the inhabitants, and about 40% of the Gross Domestic Product of the European Union. These numbers reveal the importance of both countries in Europe; however, the numbers also reveal slight differences. In this regard, there exists a lively on-going debate on centralism vs. federalism and the various impacts of it (Eilon 1999; Schlesinger et al. 2013). Although one author titled his publication *Paris and the French desert* to underline the leading role of Paris (Gravier 1949), it is important to note that efforts have been underway in France since the 1960 s to decentralise administration (Bodiguel 2006) and to give more administrative autonomy to local urban governments

(Galimberti and Pinson 2022). The decentralisation was enshrined in law in 2003 (République Française 2003). In 2005, politics have created so-called competitiveness poles spread across the country (Grandclement 2020; Theisse 2017). Even though these efforts were undertaken to reduce the dominance of Paris and the surrounding Île-de-France in comparison to other metropolitan areas and to establish so-called balanced metropolises (Rochefort 2002) , they could not stop the excessive growth of the Île-de-France region. In contrast, Germany is from the beginning on characterised by metropolitan regions mainly induced by industry, less by politics (Galland and Harrison 2020). The acceptance of these metropolitan regions as nuclei of urban development can be seen as a symbol of the paradigm shift from spatial planning to spatial development policy in Germany since the 1990s (Diller and Eichhorn 2022). In this paper, we question which of these characteristics are visible in the urban patterns imaged from space.

As economic data is prone to errors or low comparability due to the collection methods, the date of recording, the spatial reference (e.g. aggregation to administrative units) or simply the selected parameters, a comprehensive normalisation, standardisation, and aggregation is unavoidable (Eurofound 2018). Therefore, we focus on measuring central or federal structures on a different, independent data source that is free from aggregation to any political borders: settlement structures derived from remotely sensed data. As settlement structures have been shown to reflect human activity or even economic indicators (Taubenböck et al. 2017; Duque et al. 2015), we assume that settlement patterns reflect the central or federal systems in size and relations of urban agglomerations. It is one indicator proxying human activities by the restructuring of the landscape (Ehrlich et al. 2020; United Nations 2017). Built-up areas can be mapped from space by remote sensing satellites that do not distinguish between national territories (Taubenböck et al. 2023), but, they image and process any landscape according to the identical algorithm completely autonomously (Small 2021) and thus, without any influence by politics, economics, etc. Hence, the geostatistical evaluation of settlements mapped from space can be expected to deliver reliable and spatially unbiased results (Zhu et al. 2019). The temporal development though analysed in several studies (Güneralp 2020; Taubenböck et al. 2024) is not taken into account, although it would be very interesting to see the effects of the political endeavours mentioned above. We explicitly decided in favour of the GUF-DenS which provides only a snapshot of the settlements in the beginning of the 2010s on the one hand, but, on the other hand, includes the degree of impervious surfaces per pixel and therewith, a finer resolution concerning the built-up density.

In this light, we aim to compare the spatial settlement patterns of France and Germany in an nation-wide analysis. Our basic hypothesis is that the settlement structure for France is sparser (due to lower population density) and rather centralised around the capital city. For Germany, we expect a denser (due to higher population density) and more polycentric settlement structure. The 448 km long French–German border will be of particular interest as transitional region between the two systems. The focus of this study lies on the sophisticated remote sensing based technology to derive and describe urban patterns in a completely independent and consistent manner over large coverages without borders. With it, we aim to illuminate the urban patterns of the early 2010s as results of historical, political and structural developments with remote sensing data from a different perspective.

The subsequent section will briefly introduce related studies on urbanisation in Germany and France and give an overview to the state of the art. Then, the specific research questions relevant to this study are formulated. The methodology section describes the applied algorithm and the statistical measures used to evaluate possible similarities and differences. After the illustration of the results in maps and diagrams, the research questions are answered and the results a critically examined.

2 Related Work

The analysis of spatial settlement patterns in terms of monocentric or polycentric structures is subject to a diverse scientific debate. It is of course imperative to define what constitutes a centre (Anas et al. 1998; Duranton and Puga 2015; Münter and Vogelmann 2014) and which target variables shall reflect centre structures. The latter include predominantly economic variables such as businesses or job concentration (Krehl 2015; Storper and Venables 2004) or demographic variables for city size distributions (Pumain and Haag 1994). However, due to data availability issues or spatial resolutions, settlement pattern have been increasingly used to reflect on mono- or polycentric developments. Research studies in this domain have shown the capability to proxy mono- or polycentric developments by settlement patterns (Taubenböck et al. 2017). Predominantly remote sensing data have been applied to capture the settlements patterns or night-light emission have been used to proxy human activities (Zhou et al. 2022). Studies focussed on methodological developments as to how these settlement structures can best be quantitatively recorded and objectively compared. Threshold approaches (Standfuß et al. 2023), parametric (McDonald and Prather 1994; Roca Clader et al. 2009), and non-parametric approaches such as locally weighted regression models (Krehl 2018; McMillen 2001; Redfearn 2007) have been developed. Recently, Schmitt et al. (2023) introduced an approach to evaluate the multi-scale homogeneity of the settlements in a purely non-parametric way and second, to describe the built-up landscape as Gaussian Mixture Model via hierarchical multi-scale clustering, i.e. each cluster receives the parameters of a bivariate Gaussian distribution as attributes. From a geographic perspective, different spatial reference units are targeted, i.e. studies target the intra-urban (Smith 2011; Fragkias and Seto 2009), regional (Brezzi and Veneri 2015; Taubenböck and Wiesner 2015) or inter-urban centre structures (Schmidt et al. 2021; Schmitt et al. 2023). Overall, however, it must be stated that there is no scientific consensus on the approaches when it comes to the definition of centres, target variables, spatial units or methods. Against this background, studies often cannot be embedded in a broader context due to their very specific approach.

3 Conceptual Background and Motivation

In this paper, our conceptual approach bases on the fact that we define the agglomeration of settlement structures with a high built-up density over wider areas as cluster centres. For the centre identification and homogeneity analysis of the settlement pattern, we rely in this study on the approach of Schmitt et al. (2023). Thus, we define the number, size and location of centres in relation to each other as well as the homogeneity of the settlement pattern as the indicators that allow us to evaluate spatial patterns in general and to classify them as monocentric or polycentric in particular. In contrast to the known studies, we relate geographically to the settlement patterns of an entire nation, i.e. we do not only focus on metropolitan regions, major cities or other subsets. Beyond this, we geographically compare two countries with different population characteristics—Germany possesses more than twice the population density of France—and different political structures. France with its historically developed centralist organisation form should be characterised by a spatially monocentric settlement pattern in our hypothesis. Germany as federal state in comparison is presumed to show a polycentric settlement pattern.

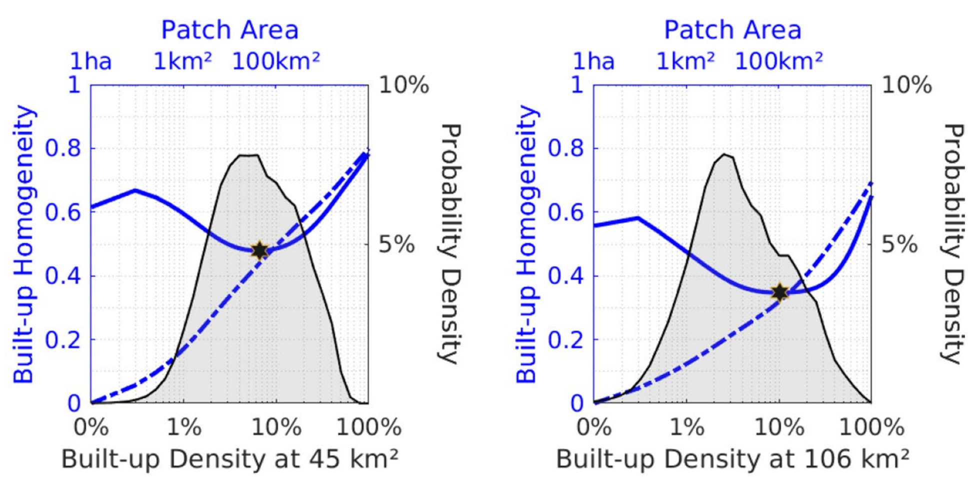
The political relevance of this inner-European comparison with respect to 60 years Elysée Treaty additionally encourages to verify evident effects of the open border policy in the Schengen area since 1985 and the economic growing together in the European Union. With respect to the literature review, we pose the following research questions for the present study:

(i) Do the nation-wide settlement patterns reflect the varying population densities?
(ii) Do the settlement patterns reflect the political structures, especially centralist versus federal?
(iii) Does the inner-European border (still) affect the settlement patterns within the border region?

These questions are answered using the methodology published by Schmitt et al. (2023) for measuring settlement landscapes. Here, slight modifications are implemented that are explained in the following two sections. The results are presented visually in maps and diagrams as well as numerically in tables. The discussion critically examines the obtained results and summarises the lessons learned for future studies.

4 Data Base and Preprocessing

Our input data are raster-based classifications of settlement areas derived from remote sensing data. The mapping product used is taken from the Global Urban Footprint suite: the



(a) Built-up density statistics for Germany (b) Built-up density statistics for France

Fig. 1 Scale-dependent homogeneity of the built-up density for Germany (left) and France (right). The solid blue line stands for built-up pixels, the dash-dotted line represents non-built-up pixels. The grey histogram shows the distribution of the built-up density at the scale of maximum heterogeneity (equal to minimum homogeneity) marked by a star and stated in the lower caption

Global Urban Footprint (GUF) and the GUF Density (GUF-DenS). Based on TerraSAR-X and TanDEM-X StripMap radar data, the GUF maps the vertical built-up structures as binary classification of settlement vs. non-settlement areas (Esch et al. 2012). The GUF-DenS layer is enhanced by using Landsat data and adds the built-up density as attribute (Esch et al. 2018) that allows for a finer distinction of urban (higher percentage of sealed surfaces) and rural settlement structures (lower percentage of sealed surfaces). This layer represents the situation during the acquisition of global elevation model by the two SAR satellites between 2011 and 2015. Multi-temporal products were not yet available at the time of our analysis. Apart from that, the multi-temporal products like the World Settlement Footprint-Evolution only contain a binary distinction in settlement yes/no (Marconcini et al. 2020).

Due to the large extension of our study site (41° N–55°N and 5° W–15° E), we decided to re-project the input data. Instead of using the GUF-DenS in geographic coordinates with a pixel spacing of about 30 m × 30 m (depending on the latitude) as archived, the settlement density is processed in the INSPIRE grid 100 (INSPIRE 2014) in Lambert's equal area projection (EPSG:3035) to assure an equal pixel area also over a large (here nation-wide) coverage. This is crucial for the comparability within and across our study sites Germany and France. Furthermore, it makes our results comparable to other studies relying on the open INSPIRE grid for Europe. The resulting uniform pixel size of 100 m × 100 m is still sufficient, because the smallest patch size of 1 km × 1 km used in the clustering process already contains about 100 pixels which is far enough to robustly derive the five parameters describing the cluster centres (X- and Y-coordinate) and their spatial expansion (X- and Y-variance as well as the X-Y-covariance).

5 Methodology

First, we aim to calculate urban clusters as densification of the settlement area on a national area-wide scale. Therefore, we apply two methodological approaches: (1) a non-parametric approach from discrete, model-free statistics, and (2) a parametric approach from continuous, model-based statistics. In this study, we rely on the methodology according to Schmitt et al. (2023). The non-parametric approach describes the homogeneity of the settled landscape in dependency of the scale. This approach reveals the perimeter of the vicinity at which the maximum heterogeneity is reached. A low homogeneity stands for a very diversified landscape of settlement pattern and density. A low perimeter indicates that already the nearer environment covers a high diversity. The parametric approach models urban agglomerations by bivariate Gaussian distributions as so-called Gaussian Mixture Model. As each cluster is characterised by its centre and size, the total number of clusters as well as the size distribution over all clusters is of interest for the assessment of a whole country. The number, sizes, and ratio of sizes to each other are indicators that point to more centralised or more polycentric settlement patterns.

5.1 Homogeneity

The non-parametric approach was applied as introduced by Schmitt et al. (2023) without any major modification. As the smallest patch of interest of 1 ha corresponds to the pixel size, the finest scale directly represents the homogeneity of settlement pixels without respect to their neighbourhood. Although this fact results in an underestimation of the homogeneity at the finest scale, it does not impede the typical global minimum observed for German cities in Schmitt et al. (2023) which is still clearly visible in Fig. 1. Both countries are processed separately, which means that pixels outside the respective national borders are not taken into account.

5.2 Gaussian Mixture Model

In the parametric approach, the maximum patch size is set to 100 km × 100 km which is adequate to capture the largest metropolitan areas in France and Germany. The smallest patch size is set to 1 km × 1 km which guarantees that smaller settlements—empirically above 1.000 inhabitants—are also detected. This means in combination with the minimum density of 0.1, that each settlement showing a mean building density above 10% over 1 km^2 is registered as urban cluster. The hierarchical multi-scale clustering process is provided as pseudo-code in Algorithm 1 for better comprehension. The threshold for the assignment to an urban cluster is set to 3.29 regarding the Mahalanobis distance which corresponds to a confidence region of 99.9%. The clusters are drawn by the ellipses of one, two, and three times the standard deviation, see Figs. 2 and 3.

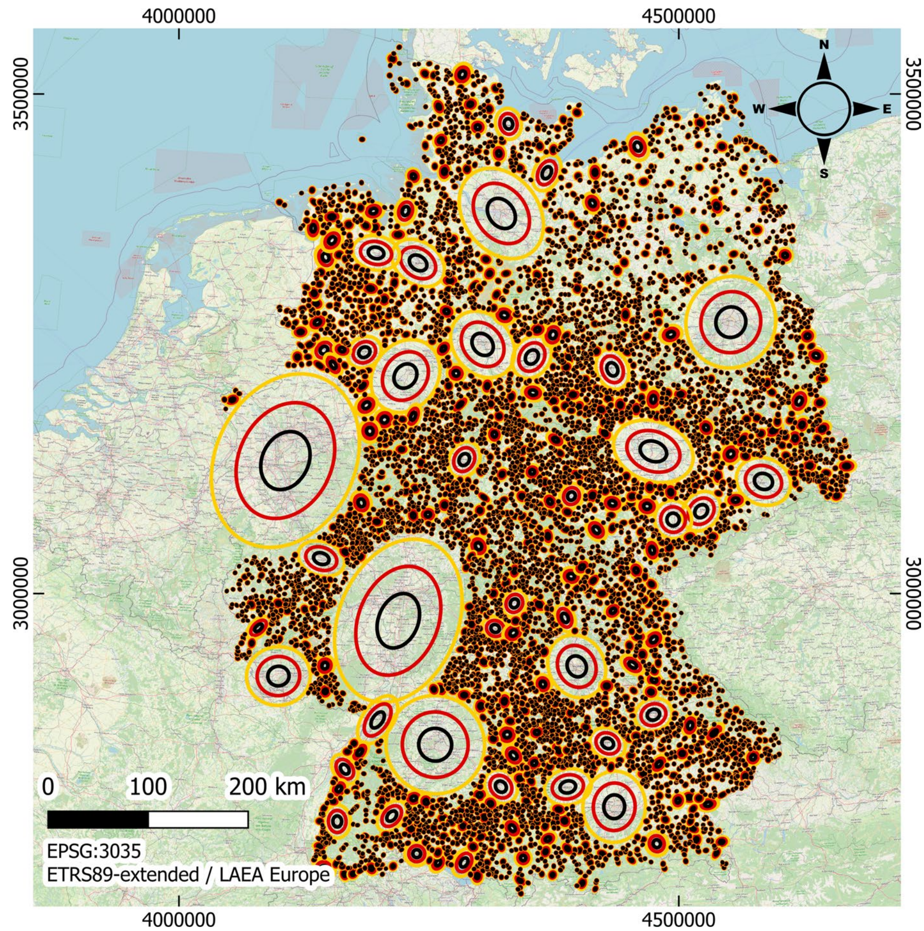


Fig. 2 Gaussian Mixture Model of urban clusters in Germany symbolised by the ellipses of simple (Black), double (Red), and triple (Gold) standard deviation underlaid with OpenStreetMap

Algorithm 1 Simplified pseudo-code of the applied hierarchical multi-scale clustering in accordance with Schmitt et al. (2023)

```
load GUF-DenS
for scale from coarse to fine do
    apply convolutions of 0^th, 1^st, 2^nd order
    while max(density) > 10% do
        mode = location of max
        center = mode + 1^st moment
        covariance = adjusted 2^nd moment
        for whole coverage do
            if distance < 3.29 then
                density=0%
            end if
        end for
        append new urban cluster to the list
    end while
end for
```

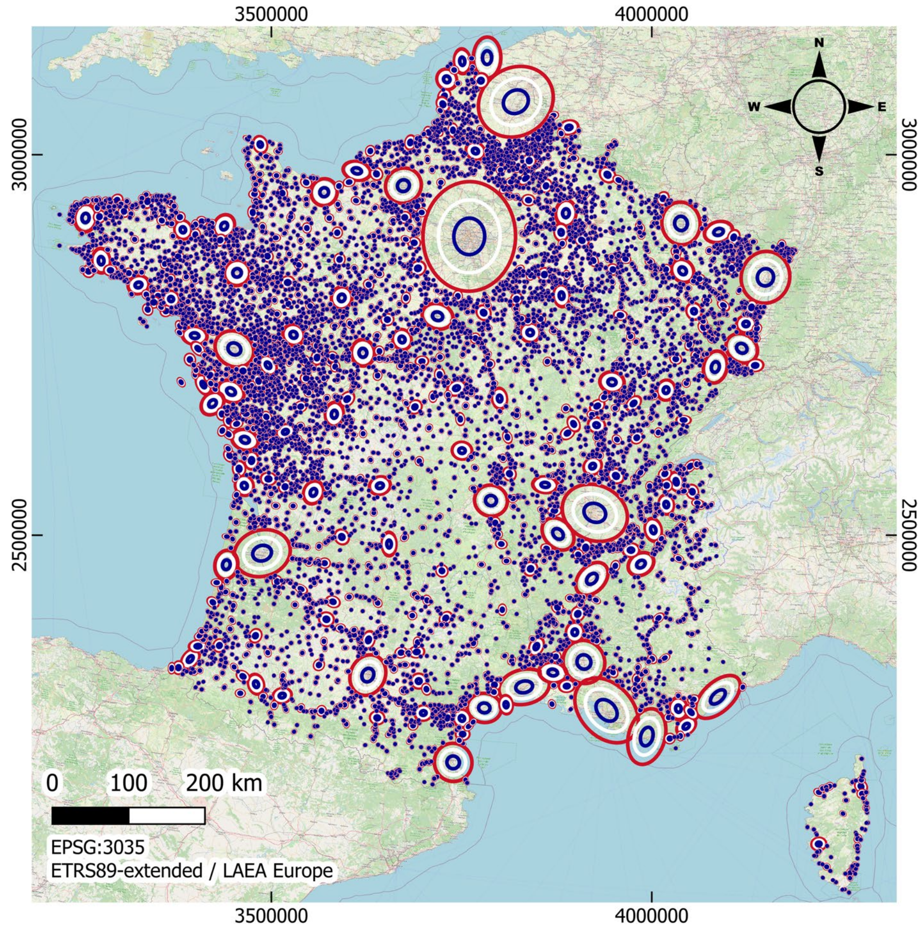


Fig. 3 Gaussian Mixture Model of urban clusters in France symbolised by the ellipses of simple (Blue), double (White), and triple (Red) standard deviation underlaid with OpenStreetMap

5.3 Statistical Analysis

The identified urban clusters are analyzed from two perspectives: the intra-cluster view represented by the individual ellipse area, and the inter-cluster relation contained in the distance to the next cluster, which stands for the density of cluster agglomerations. We apply a set of statistical measures (Table 1) in order to customise our analysis to the expected rank-size distribution. The harmonic mean typically approximates the lowest elements, i.e. the smallest cluster regarding the size—which represents the vast majority according to the rank-size rule—and highest cluster density regarding the minimum distance respectively. The geometric mean complies with the mean of the logarithmic area and distance which is imposed by the rank-size rule. The arithmetic mean is the most stable expectation value (regardless outliers) and most widely used. From the arithmetic mean, the standard deviation evolves as mean deviation. In combination, arithmetic mean and standard deviation parameterise the corresponding Gaussian distribution. The median or 50% quantile is considered to be the most robust expectation value in the presence of outliers, i.e. similar to the arithmetic mean, but in contrast to the latter, unbiased by outliers. As the robustness of quantiles decreases in both directions towards the minimum and the maximum, the 90%, 95%, and 99% are considered to describe the highest values, i.e. the largest clusters regarding the size and the lowest density regarding the minimum distance—in analogy to the harmonic mean for the lowest values. The unstable 100%-quantile—the maximum—is omitted. These results are further substantiated by a map of the Mahalanobis distance to the next cluster (Fig. 5), which is a probabilistic measure incorporating euclidean distance and size of the respective cluster. Unlike the preceding maps (Figs. 2 and 3), the Mahalanobis distance is evaluated for each pixel, i.e. also non-built-up pixels are coloured according to their probability distance to the nearest urban cluster.

5.4 Border Region

The analysis treats both countries as islands so far, i.e. as if there were no settlements outside the respective national borders. This is necessary to generate two independent—not overlapping—entities to be compared in the statistical evaluation described above. Of course, both states are not islands and the open border policy, the economic exchange, and the friendship of the states has led to cross-border ties. The closer view to the border region in Fig. 6 reflects this in the shown settlement patterns and reveals several overlaps along the French–German border. Therefore, the two separate clusterings of Germany and France now are supplemented by a third clustering of Germany and France together as union without the border in-between. We illustrate this border on/off comparison in a cartographic representation containing the ellipses of all three experiments (France, Germany, and together) in Fig. 7. Finally, we further examine the effects qualitatively by highlighting prominent examples of transnational urban agglomerations.

6 Results

In general, the analysis of the settlements according to their heterogeneity, the obvious centres and their ranking as well as their spatial distribution clearly shows that the two countries France and Germany are characterised by different settlement structures. In the border region in-between both countries, it is evident that the political border is no longer mirrored in the settlement patterns, but, that a merging has taken place. In the following, we present these results in detail and we respond to the initial research questions.

6.1 Homogeneity of Settlement Patterns

In general, the scale-dependent homogeneity shows a strong minimum below 0.5 at a patch size of 45 km^2 (about 13 km in diameter) for Germany. For France, the minimum even reaches 0.35 at a patch size of 106 km^2 (about 20 km in diameter). For comparison, Schmitt et al. (2023) stated that a minimum around 0.54 at a patch size of 44 km^2 is typical for metropolitan regions within Germany, i.e. without rural regions. Metropolitan regions in the U.S. range around a minimum of 0.61 at a patch size of 362 km^2. Both studies coincide in saying that Germany has a very small-scale structure with a relatively high heterogeneity in its settlements. In France, the heterogeneity of the settlements even exceeds the value within Germany, but at a larger scale, which means that the urban agglomerations are spread wider than in Germany. For both countries, France and Germany, the homogeneity of built-up and non-built-up pixels is almost the same at the scale of minimum homogeneity, which is extraordinary and has not been observed in previous studies so far. The density histogram indicates an almost symmetric distribution around 7% for Germany and a majority of lower densities around 2% for France. The local maximum at 0.3% for both test sites goes back to the low ratio between patch size and pixel size and has no special meaning as explained in the methodology section.

At this point, we can already answer the first research question: Yes, the settlement patterns do reflect the varying population density. The multi-scale homogeneity profile in Fig. 1 states a larger patch of minimum homogeneity for France (106 km^2) than for Germany (45 km^2). The minimum homogeneity is lower in France than in Germany which means that the urban landscape in France is more heterogeneous than in Germany. It is remarkable that the homogeneity profiles of built-up and non-built-up pixels intersect near the minimum indicated by a star in Fig. 1. One can interpret that at this scale of maximum heterogeneity an equilibrium of built-up and non-built-up pixels is achieved. In Germany, this equilibrium is already achieved at finer scales which means that there are more built-up pixels in a closer vicinity in comparison to France which clearly corresponds to the higher population density.

6.2 Gaussian Mixture Model of Settlement Patterns

Each identified urban cluster is characterised by the following parameters: mode, centre, and ellipse (derived from the covariance matrix), see Fig. 1. For the sake of clarity, only the ellipses are visualised. Figs 2 and 3 map the ellipses of simple, double, and triple standard deviation. Obviously, France has one major cluster, which is Paris. All other larger clusters, e.g. Lille, Marseille, Lyon, and Bordeaux, are significantly smaller. Germany contains two dominant clusters, the Rhine-Ruhr and the Rhine-Main (including Rhine-Neckar) metropolitan regions, followed by several large clusters of similar size like Stuttgart, Berlin, and Hamburg. In the cartographic representation, it is clear that Paris is the undisputed centre in France. In Germany, on the other hand, no dominant centre can be perceived. Additionally, the quantity of larger centres is also higher and more evenly distributed across the country's territory. This already provides a first qualitative hint to the second research question: yes, the centralist or federal structures mirror in the settlement patterns. Beyond the addressed larger centres, both maps indicate densely populated areas with lots of ellipses in close vicinity: In France, this is especially the case along the Mediterranean coast. In Germany, an arc—similar to a slightly inclined letter "G"—starting with the triangle of Nürnberg, Regensburg, and Ingolstadt, going south to Munich, and then spanning over Augsburg, Ulm, Stuttgart, Karlsruhe, Rhine–Main, Koblenz, Rhine–Ruhr, Bielefeld, Hannover, Braunschweig, Magdeburg, Leipzig–Halle to the straight line of Dresden, Chemnitz, and Zwickau is the most prominent example. Interestingly, the capital Berlin lies outside this long string of urban clusters. In both countries, however, also very sparsely populated areas are mapped: examples are the Massif Central in France or the federal

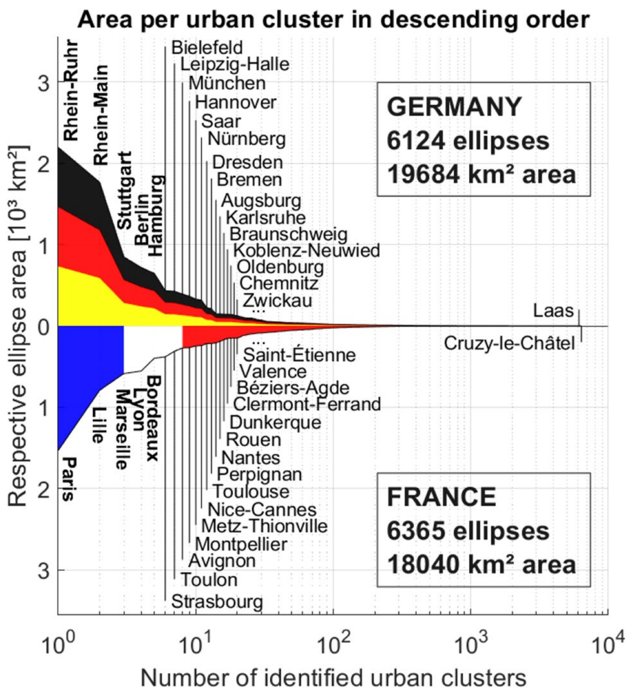


Fig. 4 Semi-logarithmic histogram of the ellipse areas in descending order for Germany and France with the names of the twenty largest identified metropolitan regions and of the smallest captured settlements. The total number of ellipses and the summed-up ellipse area is given as well

Table 1 Numerical evaluation of ellipse area and the spatial distance to the next urban cluster centre

studied parameter →	ellipse area		next center	
statistical measure ↓	[km^2]		[km]	
harmonic mean	0.4	0.4	3.4	4.0
geometric mean	0.6	0.5	3.7	4.4
arithmetic mean	3.2	2.8	4.1	5.0
standard deviation	42.0	27.6	2.7	3.1
median	0.4	0.4	3.6	4.3
90% quantile	2.8	2.3	6.2	8.5
95% quantile	6.7	5.2	7.4	10.2
99% quantile	33.5	44.7	11.1	15.5
study site →	GER	FRA	GER	FRA

state of Mecklenburg-Vorpommern in the North-East of Germany.

6.3 Statistical Analysis

To substantiate the visual inspection, the clusters now are examined with statistical parameters. Figure 4 plots the histogram of the ellipse areas in descending order in semi-logarithmic scaling. The names of the twenty largest ellipses are printed. France is characterised by 6365 urban clusters that sum up to 18,040 km^2 while Germany has 6124 urban clusters that cover 19,684 km^2.

The higher number of clusters identified in France requires that the clusters in France are smaller as shown in Tab. 1 in light of a smaller population. The mean ellipse area (simple standard deviation) in Germany reaches 3.2 km^2 while only 2.8 km^2 are covered on average in France. The striking difference between the arithmetic and geometric as well as harmonic mean underlines the large proportion of very small ellipses. A view to the larger ellipses, which are reported in the quantiles above 90%, confirms this assumption: the area values for Germany show a higher gradient and reach more than 2000 km^2 in the case of Germany whereas the largest agglomeration in France only covers about 1500 km^2.

At this point, we are able to provide a quantitative response to our second research question. Paris is measured as the major urban agglomeration in France with an ellipse of about 1531 km^2 and thus, almost twice the size of the second largest cluster which is Lille near the Belgian border with 792 km^2 ellipse area (half part even outside of France) followed by Marseille (586 km^2) and Lyon (555 km^2) with their ellipse area over 500 km^2. The identified larger clusters mainly coincide with the balanced metropolises defined in the French regional planning concept (Rochefort 2002). In Germany, there are two major clusters, i.e. the Rhine-Ruhr metropolitan area with 2194 km^2 (also partly outside Germany) and the Rhine–Main metropolitan area with 1767 km^2. This means that the primacy effect in Germany is not as pronounced as in France, as the Rhine-Ruhr region is only slightly more than 1.2 times as large as the Rhine-Main region. These two largest clusters are followed by Stuttgart (848 km^2), Berlin (719 km^2), and Hamburg (644 km^2) with their ellipse area significantly higher than 500 km^2. This fact also becomes obvious in the kurtosis of the distribution plotted in Fig. 4: leptokurtic (peaky) in the case of France and platykurtic (flat) in the case of Germany. Furthermore, the main cluster in France falls together with the capital, i.e. the undisputed political center of power, whereas the German capital Berlin ranks fourth on the list of urban clusters. The three largest clusters of Germany have importance in an economic sense, as extensive industrial zones (Rhine–Ruhr), as financial center (Rhine–Main), or as technology hubs (Stuttgart). To sum up, the observed settlement patterns obviously correspond to the administrative structures: centralised around Paris in France and dispersed over several economic centres in Germany.

With view to the first research question, the statistical evaluation shows that France counts more (6365 vs. 6124), but smaller ellipses (2.8 km^2 vs. 3.2 km^2 on average and 18,040 km^2 vs. 19,684 km^2 in total). Additionally, the distance to the next cluster centre is larger in France (5.0 km vs.

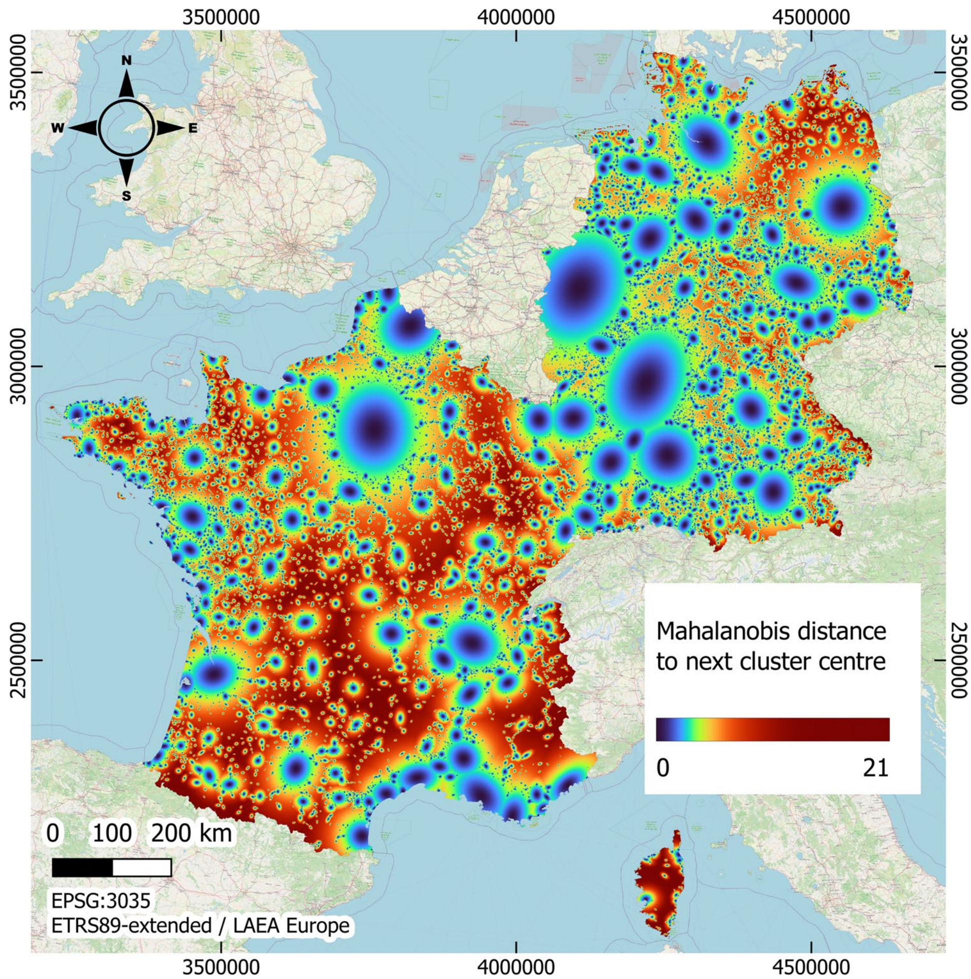


Fig. 5 Mahalanobis distance to the next urban cluster centre framed by OpenStreetMap. Blue stands for an urban cluster in close vicinity, whereas Red indicates a longer way to the next urban cluster. Urban agglomerations (in Blue) along the Rhine and Rhône river as well as the Mediterranean coast become obvious

4.1 km), which underlines the lower population density. The evaluation of the Mahalanobis distance (Fig. 5) as probabilistic distance measure further substantiates these observations: the Mahalanobis distance to the next center in France counts 5.2±3.1 (median at 4.7) whereas it only reaches 3.4±1.8 (median at 3.1) in Germany. Thus, the expected probabilistic distance to the next cluster centre is significantly longer in France than in Germany. It becomes cartographically clear that France has many rural regions that are comparatively far away from urban clusters, see extensive red areas in Fig. 5. The settlement area in Germany is much more densely populated, so that only very few regions have settlement areas with higher distances to the nearest urban clusters.

6.4 Border Region

So far, we performed a cross-country comparison. In the last part, we aim to turn specifically to the border region between both countries. Looking at the French–German border in Fig. 6, it becomes obvious that national borders do not interrupt settlement patterns: the ellipses overlay from both sides even between Alsace in France and Baden in Germany where the Rhine river forms a natural border. Therefore, a third experiment derives the clusters for France and Germany in a spatially joint, non-interrupted Gaussian Mixture Model. The map in Fig. 7 shows the transnational ellipses as blue areas. On the one hand, the ellipses perfectly coincide with the national ellipses in the interior of both countries, i.e. our results from the cross-country comparison are confirmed. On the other hand, the ellipses near the national border—now in this uninterrupted approach—merge to larger transnational urban agglomerations. In detail from the north to the south: Freyming-Merlebach in France fuses with the Saar region in Germany (2911686 N, 4096772 E). The town of Wissembourg in France and the villages of Schweigen-Rechtenbach and Schweighofen in Germany form one urban cluster (2882448 N, 4171498 E). The metropolitan region of Karlsruhe in Germany is shifted towards France and now covers also the most northern-eastern communities in Alsace (2874741 N, 4199618 E). Strasbourg in France and Offenburg in Germany compose to the main metropolitan region along the Upper Rhine (2837114 N, 4160320 E).

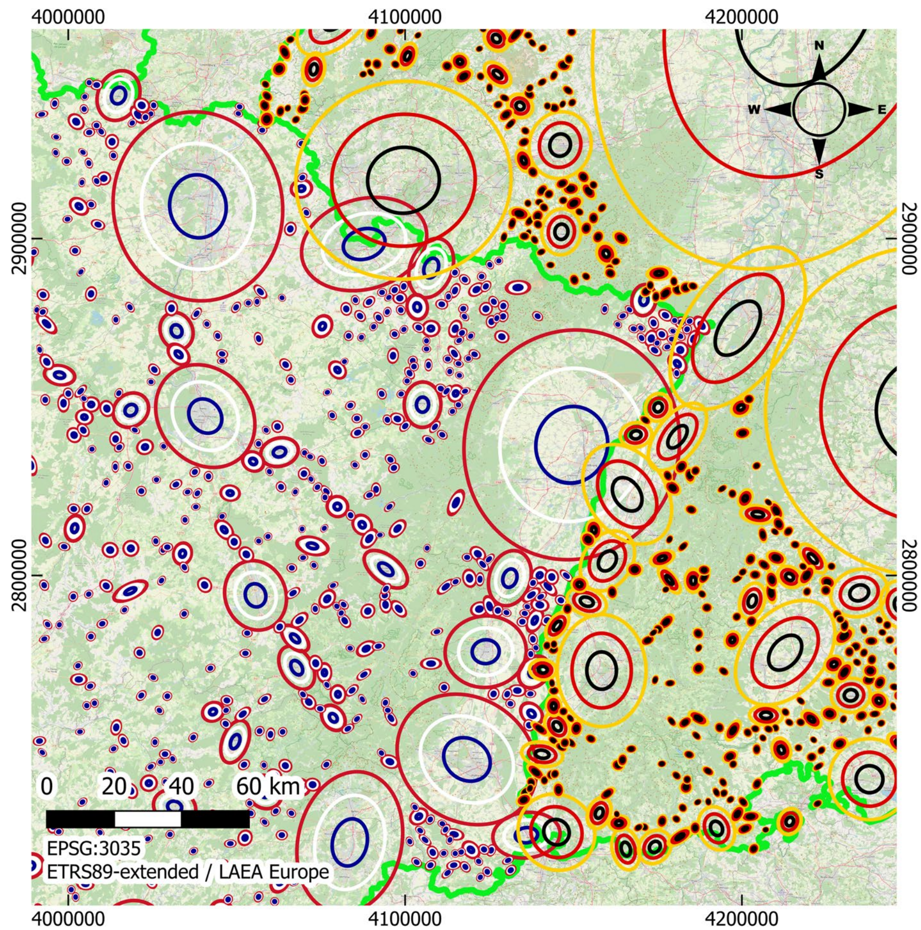


Fig. 6 Subset along the French–German border with ellipses of Gaussian Mixture Models derived from two separate clusterings of France and Germany, i.e. as if the national border (in green) was still closed. Overlapping ellipses suggest that there are transnational relations. ©EuroGeographics for the administrative boundaries Eurostat (2020)

In the same way, Neuf-Brisach and Breisach am Rhein (2771209 N, 4139114 E) as well as Saint-Louis and Weil am Rhein (2723832 N, 4140659 E) form transnational urban clusters. The cluster of Mulhouse in France now includes also Neuenburg am Rhein (2745341 N, 4118376 E). This first qualitative visual examination already reveals numerous examples that France and Germany—fortunately—are no longer separated, that the border does not interrupt settlement development, and that cross-border urban clusters have emerged.

We can finally respond to our third research question: No, the inner-European border does not affect the settlement patterns. We cannot observe any separation between Germany and France along the official border with respect to the settlement pattern based on the built-up density. On the contrary, the Upper Rhine region along the border appears more as one transnational economic artery along which numerous urban clusters line up. The separate clustering of France and Germany produces several overlapping ellipses which already indicate that the urban clusters do not end at the border. The joint European clustering identifies strong transnational metropolitan areas. It becomes most obvious in the Saar bassin (2912000 N, 4097000 E), the PAMINA region (2874000 N, 4191000 E), and the Eurodistrict Strasbourg-Ortenau (2832000 N, 4159000 E), see Fig. 7. This fits in with the concept of regional planning on both sides: strengthen the metropolitan regions as economic centres (Rochefort 2002; Diller and Eichhorn 2022). The commuter belt of Karlsruhe (e.g.) encloses several villages in the neighbouring Palatinate and in the Northern Alsace. This matches the reality because many workers commute to the industrial zones in and around Karlsruhe (City of Karlsruhe 2000). Some communities in this area like Scheibenhard(t)—directly on the border with a German and a French district – call themselves purely residential municipalities (Municipality of Scheibenhardt 2023) which indicates that most people have to commute daily to work. Nevertheless, the temporal aspect introduced by the word ”still” in the research question cannot be answered by now because our analysis bases on the mono-temporal GUF-DenS data exclusively.

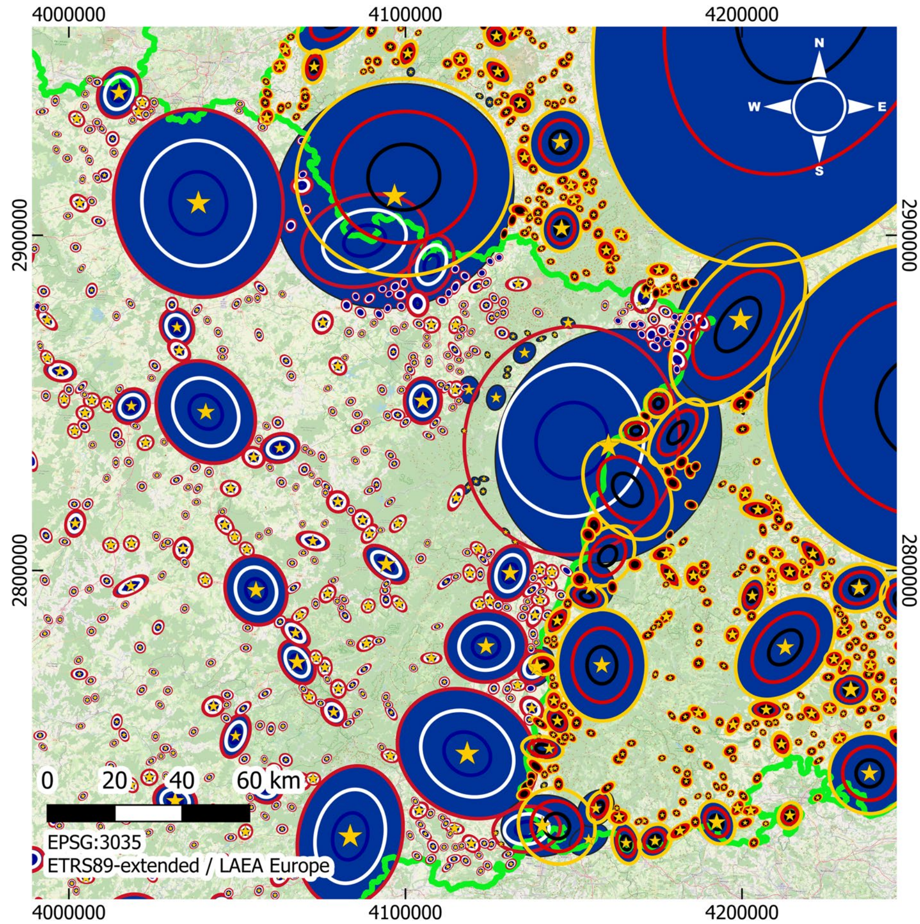


Fig. 7 Subset along the French–German border with Gaussian Mixtures Models from separate national clusterings (lines) and the joint clustering as union (Blue areas with yellow stars). Obviously, several neighbouring clusters along the national border (in green) merge to transnational metropolitan regions. ©EuroGeographics for the administrative boundaries Eurostat (2020)

7 Discussion

In this paper, we have taken an area-wide analysis of the settlement patterns based on the built-up density in the GUF-DenS data set at national scale comparing France and Germany. To do this, we systematically analysed the settlement patterns, which are described as more centralised in France and more polycentric in Germany, using cartographic and spatial quantitative approaches. We now critically assess the data set, the applied methods, the visualisation of the results, the derived statistics, and the drawn geographical interpretations.

7.1 Data-Related Aspects

The used settlement classifications (GUF and GUF-DenS) are measured with very high accuracy around 90% (Esch et al. 2018; Taubenböck et al. 2019) and high consistency of accuracy across space, especially for Europe (Klotz et al. 2016). Nevertheless, some minor classification errors remain in the input data. Thanks to the evaluation of varying image patches instead of single pixels, the impact on our analysis can be assumed as marginal. In contrast to the preceding application of this methodology, we here rely on the GUF-DenS projected to the INSPIRE 100 grid. The primary application (Schmitt et al. 2023) processed the GUF-DenS in geographical coordinates as archived. The main reason for this different preprocessing is the comparability of the derived results all over Europe. The INSPIRE 100 grid provides equal-area pixels with 1 ha, whereas the pixel size varies in the archived version. Nevertheless, the results from both approaches coincide. The non-parametric approach delivered a minimum heterogeneity of 0.54 at a patch size of 44 km^2 for metropolitan regions (standardised 200×200 km subsets) within Germany (Schmitt et al. 2023) while our new study delivers about 0.49 at 45 km^2 for the complete German territory. The reduction of the minimum homogeneity can be explained by the inclusion of rural landscapes instead of focussing on the metropolitan regions exclusively. Thus, the subsampling from the archived geographic grid to the projected INSPIRE 100 grid does not influence the non-parametric evaluation. Regarding the parametric approach, the quantitative comparison with the preceding study is not possible, because of the narrowed minimum patch size and the reduced Mahalanobis threshold which both lead to smaller and thus, more numerous ellipses.

7.2 Methodological Aspects

Both approaches prove to deliver robust results independent from the chosen spatial subset. This characteristic was already observed in a preceding study (Schmitt et al. 2023) by comparing the standardised subsets to functional urban areas. In the current study, the larger clusters clearly correspond to the ones identified in the preceding study; for instance, Berlin or the Rhine-Ruhr ellipse versus the standardised subset around Cologne published by Schmitt et al. (2023). The clusters obtained in France and Germany also correspond in principle to the results of Taubenböck et al. (2017) which are also based on remote sensing settlement area data, but were generated using a different method. This supports the plausibility of the results generated here. The varying subsets in this study (France and Germany separated by the national border in Fig. 6 and together as United Europe in Fig. 7) also prove that the only observed deviations are restricted to the border region within 50 km away from the border where the national clusters merge to transnational urban clusters. The remaining ellipses are completely identical regardless of the chosen subset with or without the border. From this we deduce, that the approach formerly developed for smaller subsets is transferable to larger coverages as well.

The processing of France and Germany together on the INSPIRE grid took 11.5 h in a MATLAB implementation on a DevCube Workstation RTX 8000 running UBUNTU 20.04 with 256GB RAM. Hence, the extension of the analysis to all countries of the European Union and selected border regions can be envisaged in future studies.

7.3 Cartographic Aspects

One major challenge is to condense the whole bunch of information in a few maps and make them intuitively understandable. Hence, the background is taken from Open Street Map to rely on a meanwhile well-known map design. The ellipses of simple, double, and triple standard deviation are drawn as contour lines not to hide the map in the background. Although individual cities cannot be distinguished in the plotted scale, one can remark that the larger clusters coincide with metropolitan regions. Instead of grading colours, we decided in favour of the respective national colours: Black, Red, Gold for Germany (Fig. 2) and Blue, White, Red for France (Fig. 3). This colouring prevents any connotation, that a randomly chosen colour might possibly imply unintentionally and further more, it supports the intuitive recognition. Therefore, it is also used in the diagram (Fig. 4) even with the typical flag design: horizontal stripes for Germany and vertical stripes for France. With focus on the border region in Fig. 7 the benefits of the described symbology becomes obvious: the ellipses can intuitively be attributed to the respective country by their colour code, but overlays along the border can also be recognised. The fact, that Red is part of both flags, does not impair the visual interpretation, because Red appears at different stages in the sequence (middle ellipse in Germany and outer ellipse in France), and the threefold concentric ellipses of one cluster in general reveal as one entity to the viewer.

With respect to the joint evaluation as union in Fig. 6, we used a solid depiction of the outer ellipses in deep Blue. The ellipse centre is marked by a golden star following the design of the European flag. This symbology induces a dominance of the ellipses derived without respecting the border line and thus, supports one of our main statements: the border line is no more visible from space. Furthermore, the blue European ellipses serve as ideal background layer for the drawn national ellipses. While the European ellipses perfectly fit the national ellipses more than about 50 km away from the border, they join several smaller ellipses from both countries along the border, which becomes clearly visible along the green line in Fig. 6. The border itself is drawn by this green line to express that it is a natural frontier along the Rhine river and a really green frontier in the north through the French–German Palatinate Forest-North Vosges Biosphere Reserve. Besides that, the colour green also stands for renewal and growth which really applies to our focus region. Regarding the Minimum Distance to the next European cluster centre in Fig. 5, we adopt a high-contrast colour map in logarithmic scale to highlight the variations mainly in the low value range impressively. The distinction by country is superfluous, but the European clusters are still apparent and again represented by deep blue ellipses in accordance to Fig. 6.

7.4 Statistical Aspects

The statistical evaluation follows two concepts to satisfy the requirements imposed by the rank-size rule and thus, the log-normal distribution of the cluster size: parametric descriptors considering the whole data set for the vast majority of smaller clusters and order-based descriptors extracting single measurements for the representation of the few larger clusters. This practice is justified by the results. As the smallest patch size is equal for both countries and given by the minimum scale of 1 km × 1 km, it is reasonable that the harmonic mean accounts 0.4 km^2 and is also equal for both countries, see Table 1. The geometric mean—as average logarithmic area—already shows a slightly higher value for Germany. This gap increases in the arithmetic mean and culminates in the 50%-, 90%, and 95%-quantiles. One discrepancy is obvious in the 99%-quantile where France exceeds the value of Germany by 11.2 km^2. This value is confirmed by Fig. 4, where the ellipse area around cluster number 62 (just below the letter *u* of the label *Zwickau*), which corresponds to the 99%-quantile, is remarkably higher in France than in Germany.

A further criticism might concern the used Mahalanobis distance, that is ambiguous in terms of physical distance because the Mahalanobis distance to a small cluster corresponds to a smaller physical distance than the identical Mahalanobis distance to a larger cluster. Assuming the minimum spatial distance as decisive measure, this point is true. But, regarding the accessibility as spatio-temporal benchmark as done in a recent study by Feicht and Schmitt (2023), the Mahalanobis corresponds quite well to the commuter belt as reported by Schmitt et al. (2023). Put simply, a larger urban agglomeration has also a larger commuter belt than a smaller one. For instance, the triple standard deviation ellipse of Munich is more or less identical with the catchment area of the Munich public transport association (Münchner Verkehrsverbund 2023). Hence, although the Mahalanobis distance does not necessarily correlate with the geodetic distance, it better approximates the perceived distance in our everyday life. To compensate the lack of geodetic meaning, we also provided the physical distance to the next centre in Table 1.

7.5 Geographic Aspects

Basically, it is clear that this study addresses the issue of centrality via a proxy. Thus, political, administrative or economic centrality cannot be evaluated in the original sense, but only indirectly by the effects of such structures on the settlement pattern. And yet, we see exactly these structures mirrored in the settlement patterns for the two countries of such different, predefining histories. In France, Paris represents a centre that outshines everything, while in Germany, no centre stands out so far. The settlement area in Germany is also much denser and the non-built-up landscape thus also more fragmented than in France. Thus, it can be confirmed that the settlement pattern is also more centralised in France —despite numerous efforts to change this — and more polycentric in Germany reflecting its federal system. We see the historically embedded different administrative systems that continue today in political or economic structures of France and Germany and are reflected in their specific settlement patterns, though we cannot infer any direct causality here. However, we must also critically note that the built-up area is a sluggish indicator of societal changes, i.e. initiated developments need at least several decades to become visible.

From a geographical point of view, it should be pointed out that although Paris is spatially the dominant centre in France, it is not the largest centre in our cross-country comparison. The Rhine-Ruhr region and the Rhine-Main region in Germany are both larger in size. These are agglomerations of numerous individual municipalities without one dominant centre. The settlement pattern thus shows that several administrative units within the urban clusters are overcome and larger centres have emerged beyond the political entities. The second-tier centres in Germany—such as Stuttgart, Berlin, Hamburg and many more—are spatially also more evenly distributed across the country than in France. The second-tier centres in France are most of all found at the margin, i.e. the coasts (Bordeaux and Marseille), the inner-European borders (Lille and Strasbourg), and in the Rhône valley (Lyon and others). They represent some of the balanced metropolises and competitiveness poles pursued by the French regional planning of the last decades (Rochefort 2002; Theisse 2017). Anyways, there is a very large geographical gap between the capital Paris and the subordinate major centres. Thus, one can conclude that in France, Paris is the dominant centre—spatially, politically, and economically. In Germany, on the other hand, these structures are distributed differently. The political centre is Berlin, but spatially only number four, the economic centres are spread across the country and the spatial settlement patterns are also more equally distributed.

In addition, it is interesting to see, how settlement patterns along the open borders between both countries grow together and form cross-border agglomerations. This confirms a large-scale analysis of settlement patterns on European level showing the coalescence of the settlement band along the so-called Blue Banana in Europe across open borders within the Schengen Agreement (Taubenböck et al. 2017). But, it also shows, how political friendship and economic inter-dependencies in the border region are reflected in the coalescence of settlement patterns. This study shows the different settlement patterns of the two countries. However, a normative evaluation of these settlement patterns must be refrained from here. Rather, this study can be specifically empirically supportive in normative approaches.

7.6 Future Aspects

This study is based on the current state of the settlement pattern, i.e. the question of whether the settlement patterns of both countries have developed in a centralised or polycentric direction in recent years has not yet been clarified. As we analysed the GUF-DenS that shows the situation around 2015, we cannot extrapolate neither in the past nor in the future. This particular aspect has to be focussed in a follow-on study that evaluates the temporal evolution, e.g. based on the World Settlement Footprint-Evolution (WSF-E) according to Marconcini et al. (2020) that is publicly available for the years 1985 until 2015 (Taubenböck et al. 2024) and additionally for the year 2019. As the WSF-E only contains a binary settlement mask for the respective years instead of a fine sampled built-up density as provided by the GUF-DenS, we decided in favor of the GUF-DenS for this pilot study in the full knowledge that the temporal evolution cannot be assessed. Another reason for choosing the GUF-DenS is the positive experience with the GUF-DenS in a preceding comparative study on metropolitan areas in Germany and the USA which provided reasonable results on the settlement patterns (Schmitt et al. 2023). The temporal evolution thus will be subject to further studies that base on the WSF-Evolution or built-up indices (e.g. LEAI as recently published by Schollerer et al. (2022)) drawn from yearly mosaics of Landsat and/or Sentinel-2 data. Using this database, the investigation period could possibly extended back to the seventies until now and would as expected document the continuous growing together of the European Union.

8 Conclusion

This study adapts an innovative technique for the geostatistical assessment of rather small image subsets of the Global Urban Footprint-Density (GUF-DenS) to the processing of a large coverage, for instance the complete European territory of France and Germany. For consistency reasons, the INSPIRE grid 100 in Lambert's Equal Area projection is imposed to the GUF-DenS first. The non-parametric analysis states a higher heterogeneity at larger patches for France which corresponds to the lower population density. The parametric approach delivers less, but on average larger clusters for Germany. The undisputed dominant cluster of France is Paris, whereas Germany is characterised by several larger clusters of similar size. This fact can be related to the central and federal administrative systems respectively induced by the individual history. Regarding the border region, urban clusters from both sides meanwhile merge to transnational urban agglomerations, i.e. the proclaimed Eurodistricts are indeed visible from space. The temporal development of the possibly ongoing process of growing together within the European Union will be subject to future studies .

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42489-024-00173-x.

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Data availability The urban ellipses of France and Germany (separately and together as union) derived from the Global Urban Footprint - Density, shown in Figs. 2, 3, 6 & 7 and supporting Figs 4 & 5 are provided as supplementary material under Open Data Commons Attribution License.

Declarations

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Conflict of interest The authors declare no Conflict of interest

References

Anas A, Arnott R, Small K (1998) Urban spatial structure. J Econ Lit 36(3):1426–1464

Brezzi M, Veneri P (2015) Assessing polycentric urban systems in the OECD: Country, regional and metropolitan perspectives. Eur Plan Stud 23(6):1128–1145. https://doi.org/10.1080/09654313.2014.905005

Bodiguel JL (2006) La DATAR: quarante ans d'histoire. In: Revue française d'administration publique, vol 119, no 3, pp 401–414. https://shs.cairn.info/revue-francaise-d-administration-publique-2006-3-page-401?lang=fr. Accessed 12 Sept 2024

City of Karlsruhe (2000) Statistical yearbook [German], https://transparenz.karlsruhe.de/dataset/jahrbuch. Accessed 12 Sept 2024

Daniel U, Krumeich G, Anklam E, Lindner-Wirsching A, Mehrkens H and Schröder J (2004) *Frankreich und Deutschland im Krieg (18.-20. Jahrhundert): Zur Kulturgeschichte der europäischen "Erbfeindschaft"* [German]. https://doi.org/10.24355/dbbs.084-200603150100-35

Diller C, Eichhorn S (2022) 25 Jahre Metropolregionen in Deutschland im Spagat zwischen Raumordnung und Raumentwicklung. Ein Klassifizierungsvorschlag. Standort 46:16–23. https://doi.org/10.1007/s00548-021-00760-4

Duggan LG, Hamerow S, Barkin K, Strauss G, Heather PJ, Wallace-Hadrill JM, Sheehan JJ, Schleunes KA, Turner HA, Geary PJ, Elkins TH, Bayley CC, Kirby GH, Leyser KJ, Berentsen WH (2022) Germany, Encyclopedia Britannica, Invalid Date, https://www.britannica.com/place/Germany. Accessed 6 Apr 2023

Duggan LG, Hamerow S, Barkin K, Strauss G, Heather PJ, Wallace-Hadrill JM, Sheehan JJ, Schleunes KA, Turner HA, Geary PJ, Elkins TH, Bayley CC, Kirby GH, Leyser KJ, Berentsen WH (2023) European Coal and Steel Community, Encyclopedia Britannica, https://www.britannica.com/topic/European-Coal-and-Steel-Community. Accessed 12 Sept 2024

Duque JC, Patino JE, Ruiz LA, Pardo-Pascual JE (2015) Measuring intraurban poverty using land cover and texture metrics derived from remote sensing data. Landsc Urban Plan 135:11–21. https://doi.org/10.1016/j.landurbplan.2014.11.009

Duranton G, Puga D (2015) Urban land use. In: Duranton G, Henderson JV, Strange WC (eds) Handbook of regional and urban economics, vol 5. Elsevier, Amsterdam, pp 467–560

Ehrlich D, Balk D, Sliuzas R (2020) Measuring and understanding global human settlements patterns and processes: innovation, progress and application. Int J Digit Earth 13(1):2–8. https://doi.org/10.1080/17538947.2019.1630072

Eilon S (1999) Centralism versus Federalism. In: Management strategies. Springer, Boston. https://doi.org/10.1007/978-1-4615-4585-9_18

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. J Appl Remote Sens 6(1):21

Esch T, Üreyen S, Zeidler J, Hirner A, Asamer H, Metz-Marconcini A, Marconcini M (2018) Exploiting big earth data from space—first experiences with the TimeScan processing chain. Big Earth Data. https://doi.org/10.1080/20964471.2018.1433790

Eurofound (2018) Measuring varieties of industrial relations in Europe: a quantitative analysis, Publications Office of the European Union, Luxembourg. https://www.eurofound.europa.eu/en/publications/2018/measuring-varieties-industrial-relations-europe-quantitative-analysis. Accessed 12 Sept 2024

European Commission (1997) Council Regulation (EC) No 1103/97 of 17 June 1997 on certain provisions relating to the introduction of the euro, Official Journal L 162, 19 June 1997 P. 0001 - 0003. European Communities, 19 June 1997. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31997R1103:EN:HTML. Accessed 12 Sept 2024

European Commission (2023) Schengen Area, Migration and Home Affairs, https://home-affairs.ec.europa.eu/policies/schengen-borders-and-visa/schengen-area_en. Accessed 12 Sept 2024

European Council (2015) Franco-German relationship as engine of EU integration, https://www.consilium.europa.eu/en/documents-publications/library/library-blog/posts/franco-german-relationship-as-engine-of-eu-integration/. Accessed 12 Sept 2024

European Union (2023) History of the EU, https://european-union.europa.eu/principles-countries-history/history-eu_en. Accessed 12 Sept 2024

Eurostat/GISCO (2020) Administrative or Statistical Units – Countries, https://ec.europa.eu/eurostat/web/gisco/geodata/administrative-units. Accessed 12 Sept 2024

Feicht T, Schmitt A (2023) Anamorphic visualization of the space-time-paradigm by geodetic network adjustment. KN J Cartogr Geogr Inf 73:39–50. https://doi.org/10.1007/s42489-022-00124-4

Fragkias M, Seto K (2009) Evolving rank-size distributions of intra-metropolitan urban clusters in South China. Comput Environ Urban Syst 33(3):189–199

France Diplomacy (2023) Elysée Treaty - The Elysée Treaty in six questions, Ministry for Europe and Foreign Affairs. https://www.diplomatie.gouv.fr/en/country-files/germany/france-and-germany/elysee-treaty/. Accessed 12 Sept 2024

Franke U, Puglierin J (2020) The big engine that might: How France and Germany can build a geopolitical Europe, European Council on Foreign Relations. https://ecfr.eu/wp-content/uploads/the_big_engine_that_might_how_france_and_germany.pdf. Accessed 12 Sept 2024

Galland D, Harrison J (2020) Conceptualising metropolitan regions: how institutions, policies, spatial imaginaries and planning are influencing metropolitan development. In: Zimmermann K, Galland D, Harrison J (eds) Metropolitan regions, planning and governance. Springer, Cham. https://doi.org/10.1007/978-3-030-25632-6_1

Galimberti D, Pinson G (2022) Urban policies in France: stronger metropolises and steering state. Comparative studies of political agendas. In: Gelli F, Basso M (eds) Identifying models of national urban agendas. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-031-08388-4_2

Grandclement A (2020) Les pôles de compétitivité: d'une géographie de l'innovation à une géographie de la production. Géoconfluences, Décembre 2020. https://geoconfluences.ens-lyon.fr/informations-scientifiques/dossiers-regionaux/la-france-des-territoires-en-mutation/articles-scientifiques/poles-de-competitivite. Accessed 12 Sept 2024

Gravier JF (1949) Paris et le désert français, Paris, 1947. In: Mise en valeur de la France, Paris, 1949 Dessus (G.), George (P.), Weulerse (J.), Matériaux pour une géographie volontaire de l'industrie française, Paris, 1949

Güneralp B, Reba M, Hales BU, Wentz EA, Seto KC (2020) Trends in urban land expansion, density, and land transitions from 1970 to 2010: a global synthesis. Geograph Sci Urban Plan Sch (SGSUP). https://doi.org/10.1088/1748-9326/ab6669

Hoepel T (2012) Der deutsch-französische Grenzraum: Grenzraum und Nationenbildung im 19. und 20. Jahrhundert. In: Europäische Geschichte Online (EGO) [German], Leibniz-Institut für Europäische Geschichte (IEG), Mainz. http://www.ieg-ego.eu/hoepelt-2012-de. Accessed 12 Sept 2024

INSPIRE Working Group (2014) D2.8.I.2 data specification on geographical grid systems—technical guidelines. https://inspire.ec.europa.eu/id/document/tg/gg. Accessed 12 Sept 2024

Klotz M, Kemper T, Geiß C, Esch T, Taubenböck H (2016) How good is the map? A multi-scale cross-comparison framework for global settlement layers: evidence from Central Europe. Remote Sens Environ 178:191–212. https://doi.org/10.1016/j.rse.2016.03.001

Krehl A (2015) aUrban spatial structure: an interaction between employment and built-up volumes. Reg Stud Reg Sci 2(1):289–307. https://doi.org/10.1080/21681376.2015.1034293

Krehl A (2018) Urban subcentres in German city regions: identification, understanding, comparison. Pap Reg Sci 97(1):79–105. https://doi.org/10.1111/pirs.12235

Loughlin J (2007) Centralization and decentralization in French history. In: Subnational government French politics, society and culture series. Palgrave Macmillan, London. https://doi.org/10.1057/9780230210622

Marconcini M, Metz-Marconcini A, Üreyen S, Palacios-Lopes D, Hanke W, Bachofer F, Zeidler J, Esch T (2020) Outlining where humans live, the World Settlement Footprint 2015. Sci Data 7:242. https://doi.org/10.1038/s41597-020-00580-5

McDonald J, Prather P (1994) Suburban employment centres: the case of Chicago. Urban Studies, 31, 201-218. https://www.jstor.org/stable/43196088. Accessed 12 Sept 2024

McMillen DP (2001) Nonparametric employment subcenter identification. J Urban Econ 50(3):448–473. https://doi.org/10.1006/juec.2001.2228

Münchner Verkehrs- und Tarifverbund GmbH (2023) Verkehrslinienplan Region München [German], https://www.mvv-muenchen.de/fileadmin/mediapool/03-Plaene_Bahnhoefe/VLP/Verkehrslinienplaene_Muenchen_und_Region/MVV_VLP_Region.PDF. Accessed 12 Sept 2024

Münter A, Volgmann K (2014) The metropolization and regionalization of the knowledge economy in the multi-core Rhine-Ruhr Metropolitan Region. Eur Plan Stud 22(12):2542–2560. https://doi.org/10.1080/09654313.2013.844776

Municipality of Scheibenhardt (2023) Portrait: Scheibenhardt - the attractive residential municipality between Bienwald forest and Lauter river [German]. http://scheibenhardt.de/index.php/portraet. Accessed 12 Sept 2024

Poptcheva EM (2015) The Franco-German relationship in the European Union—a short overview, European Parliamentary Research Service (EPRS). https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568359/EPRS_BRI%282015%29568359_EN.pdf. Accessed 12 Sept 2024

Price R (2014) A concise history of France (3rd edn., Cambridge Concise Histories). Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139084710

Pumain D, Haag G (1994) Spatial patterns of urban systems and multifractality. Mitteilungen des SFB 230, vol 9, pp 243–252. https://shs.hal.science/halshs-01625406/file/2302-63.pdf. Accessed 12 Sept 2024

Redfearn C (2007) The topography of metropolitane employment: identifying centers of employment in a polycentric urban area.

J Urban Econ 61(3):519–541. https://doi.org/10.1016/j.jue.2006.08.009

République Française (2003) LOI constitutionnelle n° 2003-276 du 28 mars 2003 relative à l'organisation décentralisée de la République. https://www.legifrance.gouv.fr/dossierlegislatif/JORFDOLE000017760406/. Accessed 12 Sept 2024

Roca Cladera J, Marmolejo Duarte CR, Moix M (2009) Urban structure and polycentrism: towards a redefinition of the sub-centre concept. Urban Studies 46(13):2841–2868. https://doi.org/10.1177/0042098009346329

Rochefort M (2002) Des métropoles d'équilibre aux métropoles d'aujourd'hui. Strates [En ligne], Hors-série | 2002, mis en ligne le 02 mai 2005, consulté le 08 septembre 2020. http://journals.openedition.org/strates/515; https://doi.org/10.4000/strates.515. Accessed 12 Sept 2024

Schlesinger R (2013) Federalism in Central and Eastern Europe, International Library of Sociology, Taylor & Francis, ISBN: 9781136231155, p 544. https://archive.org/details/dli.ernet.2529. Accessed 12 Sept 2024

Schmidt S, Li W, Carruthers J, Siedentop S (2021) Planning institutions and urban spatial patterns: evidence from a cross-national analysis. J Plan Educ Res. https://doi.org/10.1177/0739456X211044203

Schmitt A, Uth P, Standfuß I, Heider B, Siedentop S, Taubenböck H (2023) Quantitative assessment and comparison of urban patterns in Germany and the United States. Comput Environ Urban Syst 100:101920. https://doi.org/10.1016/j.compenvurbsys.2022.101920

Small C (2021) Grand challenges in remote sensing image analysis and classification. Front Remote Sens 1:2021. https://doi.org/10.3389/frsen.2020.605220

Smith DA (2011) Polycentricity and sustainable urban form. An intra-urban study of accessibility, employment and travel sustainability for the strategic planning of the London region (Dissertation). University College London, London, UK. https://discovery.ucl.ac.uk/id/eprint/1324180/. Accessed 12 Sept 2024

Schollerer L, Schmitt A, Wendleder A, Rogginger S (2022) Regular investigation of construction activities from space based on open satellite imagery. zfv 3/2022 (147. Jg.), Wißner-Verlag, 168-180. https://geodaesie.info/images/zfv/147-jahrgang-2022/downloads/zfv_2022_3_Schollerer_et-al.pdf. Accessed 12 Sept 2024

Standfuß I, Geiß C, Kühnl M, Droin A, Mast J, Wurm M, Siedentop S, Heider B, Taubenböck H (2023) In the tension between large-scale analysis and accuracy—identifying and analysing intra-urban (sub-)centre structures comparing official 3D-building models and TanDEM-X nDSMs. Comput Environ Urban Syst. https://doi.org/10.1016/j.compenvurbsys.2023.101953

Storper M, Venables AJ (2004) Buzz: face-to-face contact and the urban economy. J Econ Geogr 4(4):351–370. https://doi.org/10.1093/jnlecg/lbh027

Taubenböck H, Wiesner M (2015) The spatial network of megaregions—types of connectivity between cities based on settlement patterns derived from EO-data. Comput Environ Urban Syst 54:165–180. https://doi.org/10.1016/j.compenvurbsys.2015.07.001

Taubenböck H, Ferstl J, Dech S (2017) Regions set in stone—classifying and categorizing regions in Europe by settlement patterns derived from EO-data. ISPRS Internatl. J Geo-Inform 6(2):1–27. https://doi.org/10.3390/ijgi6020055

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 Sens Environ. https://doi.org/10.1016/j.rse.2019.111353

Taubenböck H, Otto C, Gülzau F, Mau S (2023) Border regions across the globe: analyzing border typologies, development dynamics, economic and political disparities. Appl Geogr. https://doi.org/10.1016/j.apgeog.2022.102866

Taubenböck H, Mast J, Geiß C, Wurm M, Esch T, Seto K (2024) Global differences in urbanization dynamics from 1985 to 2015 and outlook considering IPCC climate scenarios. Cities. https://doi.org/10.1016/j.cities.2024.105117

Theisse J (2017) Des pôles de compétivité performants et structurants pour les territoires. In: En Bref. Une publication du Commissariat général à l'égalité des territoires (CGET). ISSN 2492-5012. https://temis.documentation.developpement-durable.gouv.fr/docs/Temis/0086/Temis-0086406/86406.pdf. Accessed 12 Sept 2024

Umbach M (2002) German Federalism: past, present and future (New Perspectives in German Political Studies), Palgrave Macmillan, ISBN 13: 9781349428625. https://link.springer.com/book/10.1057/9780230505797. Accessed 12 Sept 2024

United Nations (2017) Housing and urban development in the Economic Commission for Europe Region, UNECE and UN-Habitat, ISBN: 978-92-1-132744-1, https://unece.org/fileadmin/DAM/hlm/projects/HIII_Regional_Report/HabitatIII-Regional-Report-Europe-Region.pdf. Accessed 12 Sept 2024

Zhou Y, He X, Zhu Y (2022) Identification and evaluation of the polycentric urban structure: an empirical analysis based on multi-source big data fusion. Remote Sens. 14:2705. https://doi.org/10.3390/rs14112705

Zhu Z, Zhou Y, Seto K, Stokes E, Deng C, Pickett STA, Taubenböck H (2019) Understanding an urbanizing planet: strategic directions for remote sensing. Remote Sens Environ 228:164–182. https://doi.org/10.1016/j.rse.2019.04.020