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# Geovisualization of artificial land use in European cities in 2006, with urban scaling laws

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## 1. Introduction

More and more people are living in urban areas: according to the World Bank (2020<sup>1</sup>), the urban population worldwide rose from 47% in 2000 to 56% in 2020. This population growth is accompanied by an even more rapid process of land artificialization: world annual built-up growth was 1.39% between 2000 and 2015 (with a factor of 1.13 between world annual built-up growth and population growth) (Denis, 2020). Land artificialization takes place mainly through two simultaneous phenomena: the densification of urban infill and urban sprawl (Béchet et al., 2017). Urban sprawl often takes the form of urbanization fronts from the outskirts, due to the relative availability of land (EEA, 2006). Surprisingly, cities with declining populations also experience an increase in urban sprawl (Reckien and Karecha, 2007; Sidentop and Fina, 2010; Salvati et al., 2013). Urban sprawl generally results in a decrease in the population density of urban space (Burchell and Galley, 2003) as one moves away from the center. This is why, despite the growth in population and land artificialization, the world's average urban density has decreased, from 2775 inhabitants per km<sup>2</sup> in 1990 to 2756 inhabitants per km<sup>2</sup> in 2015 (Denis, 2020). Land artificialization appears to be taking place at unequal densities.

In the future, urban areas are projected to face more land use pressures such as a decrease in agricultural productivity. An estimated loss of six million tons of wheat production in the EU

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<sup>1</sup> <https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS>

occurred between 1990 and 2006 (Gardi et al., 2015). The continuous expansion of cities and its impacts on the urban form disrupts the way cities function by revealing sustainability problems. Historically, cities have been built-up on fertile soils, and urban sprawl usually occurs on the most productive agricultural land (Ferrara et al., 2014). Artificial land use presents a significant challenge for urban policy (EEA, 2006), particularly in peri-urban areas where land use changes can happen rapidly and are influenced by systematic processes of change (Tavares et al., 2012). For example, the progressive urbanization of the urban fringes leads to increasing commuting times (Weiss et al., 2018) and higher levels of traffic congestion, leading in turn to more air pollution concomitantly with an increase in urban heat islands (EEA, 2010). The combination of soil artificialization in urban areas and climate change (IPCC, 2021) further intensifies the challenges associated with natural risk management. For example, the artificialization of soils reduces their permeability (Desailly et al., 2009), which in turn, mechanically heightens the risks of flooding and generates adverse environmental impacts (Czamanski, 2008).

The study of the spatial distribution of artificial land use has been limited, with the focus often being on the opposition between the central city and its periphery. However, it is crucial to gain a better understanding of the forms and dynamics of land artificialization. We know that there is continuous artificialization in Europe, and we also have a good knowledge of the phenomena that drive this artificialization. But, the current problem is that we still have an overly schematic vision of the location where this artificialization occurs on an intra-urban scale. There is still no real cross-over between intra- and inter-urban approaches. This requires a more detailed analysis of land artificialization at a local level, to identify how land use is changing and how this is impacting different parts of the city. Furthermore, spatial analysis can help identify areas that are particularly vulnerable to soil sealing, such as ecologically sensitive areas or low-income communities. Such information can be used to develop more effective and equitable policies for managing soil sealing and reducing its impacts. In short, a spatial and geographical analysis of artificial land use in urban areas is crucial for creating a more comprehensive understanding of this complex issue and promoting sustainable urban planning.

Cities undergo similar processes of transformation over time. For example, they have adapted their spatial organization to the evolution of transport modes (Guérois and Pumain, 2008). To gain a deeper understanding of artificial land use in urban areas, it is therefore also important to compare cities and identify general forms and patterns on a large scale. Our work seeks to

bridge the gap between studies that lack a spatial perspective of land artificialization within cities and those that examine land artificialization outside of urban areas, but don't necessarily take into account the dynamics within the urban core.

We adopt a specific analytical approach to better understand the phenomenon of land artificialization and its spatialization. We use a comparative analysis of the evolution of land use in the largest European cities, focusing on center-periphery organization. The purpose of our study is to closely examine changes of artificial land usage in urban environments, particularly in relation to the distance from the main city center. The center-periphery analysis constitutes the first spatial differentiation for urban areas (Guérois and Pumain, 2008). The choice of a radial analysis is also well suited to the general patterns of organization of European cities. We conduct comprehensive evaluations of cities using a reference center within each urban environment to study land distribution in its entirety using this radial approach. The heterogeneity of land use is explained by distance-to-center effects (transportation costs and center-periphery developments) that impact artificial land use (Alonso, 1964).

We use urban scaling laws to compare cities that are difficult to match in terms of size. Urban scaling laws make it possible to transform a set of objects from one spatial scale to another without changing their structure, thus facilitating comparative analyses of cities (Batty, 2015). In a nutshell, urban scaling laws aggregate cities on the same basis to abstract from the size effect. The combination of these two types of analysis (center-periphery and scaling laws) offers a new perspective on cities, notably through systematic inter-city comparison. The methods section (2.2) will explain these two methodological approaches.

In this paper, we introduce an open-source web platform we have developed to enable users to view and compare the radial profiles of land artificialization for 305 major European cities in 2006. The platform is designed to be user-friendly and accessible to non-specialists, with interactive choices and city selections. The use of dashboards is aimed at facilitating knowledge transfer between the scientific community and urban planners (O'Brien and Cheshire, 2015, Kourtit and Nijkamp, 2018 and Sarikaya et al., 2019), as it has been shown to increase user engagement through interactive and adaptive content (Christophe, 2019). By combining radial profiles and urban scaling laws, the tool offers an innovative perspective on cities and presents an opportunity to gain insights into land artificialization in European cities.

## 2. Methods

### 2.1. Data

The web application presented here focuses on artificial land use in 305 European Functional Urban Areas (FUAs) with more than 100,000 inhabitants in 2006. We use the Copernicus Urban Atlas 2006 land use database at 5 m resolution and the Geostat population grid at 1 km resolution. For the whole European Union, we combine this dataset with the 1 km<sup>2</sup> population grid of Geostat for 2006 to obtain the population in each FUA.

Artificial land use, as defined in this paper, encompasses all land use categories in the Urban Atlas 2006, excluding water areas, agricultural spaces, urban green spaces, and forests. The radial profiles show the distribution of artificial land use categories as a function of distance from the center of each city.

### 2.2. Radial analysis and urban scaling laws

City definition is a crucial question and is a subject of debate (Louf and Barthelemy, 2014). There is not yet a homogeneous definition and a consensus to delimit urban areas. Indeed, the lack of a clear definition of cities on a global scale and the collection of data creates problems for in-depth analysis of these urban systems (Rybski et al., 2019). In this paper, we adopt a morphological definition of cities, referring not only to their administrative units but also including their peripheral areas to consider the overall city's structure.

Even in polycentric cities or cities with large sub-centers, there is often a main center with the highest population density (Griffith and Wong, 2007). To be able to compare our extensive dataset, we designate the city hall as the reference geographical center. Then, concentric rings of 141 m ( $100\sqrt{2}$ ) are made around the city hall to calculate the share of land use in these rings.

However, this circular center-periphery approach smoothes out non-radial structures such as sub-centers nested within the urban structure, and it is also a problem for cities near each other and coastal cities. As a matter of fact, the coast, which is a strong geographical constraint, changes the center-periphery structure and breaks the circular symmetry. In addition, historical and cultural aspects specific to each city, singular urban planning policies, and boundary effects explain some of the differences between urban areas and the way a city

develops. The radial analysis and urban scaling laws are therefore simplifying tools to analyze cities and urban forms.

Urban scaling laws make it possible to abstract the effect of city size and thus compare them on an aggregate basis (Pumain, 2004). However, urban scaling laws studied previously are aspatial in most cases, relating city population to GDP, wages, and the number of crimes or patents (Bettencourt, 2013). The scaling exponents which take the form of a power law, show a covariation between the absolute urban quantity  $Y$  and the total population  $N$  in a city  $i$  (Shalizi, 2011):

$$Y_i = \alpha * N_i^\beta$$

*Equation 1. General urban scaling law equation*

where  $\alpha$  represents a time-dependent normalization constant, and  $\beta$  is the scaling exponent studied (Cottineau, 2017).

Now, through the work of Lemoy and Caruso (2020), thanks to the rescaling of distances from the center, the comparison of the evolution of artificial land use becomes possible for cities of different sizes. Their research demonstrates that the internal structure of cities follows a homothetic scaling relationship in relation to population. Homothety is a mathematical transformation that multiplies all distances by a fixed factor while preserving shapes.

The scaling relationships found by Lemoy and Caruso (2020) suggest simple new definitions for cities of all sizes, which are more consistent using the land use scale as a reference.

In their paper, each European city is rescaled by a factor  $k$  that is the ratio of the population of London  $N_{London}$  (London being the European city with the largest population in Europe, chosen as the reference city) to the population  $N$  of the studied city, all to the square root:

$$k = \sqrt{\frac{N_{London}}{N}} = \left(\frac{N_{London}}{N}\right)^{1/2}$$

*Equation 2. The equation to obtain the scaling factor for land uses*

In this equation, the exponent  $1/2$  is similar to  $\beta$  in the fundamental urban scaling laws equation (equation 1).

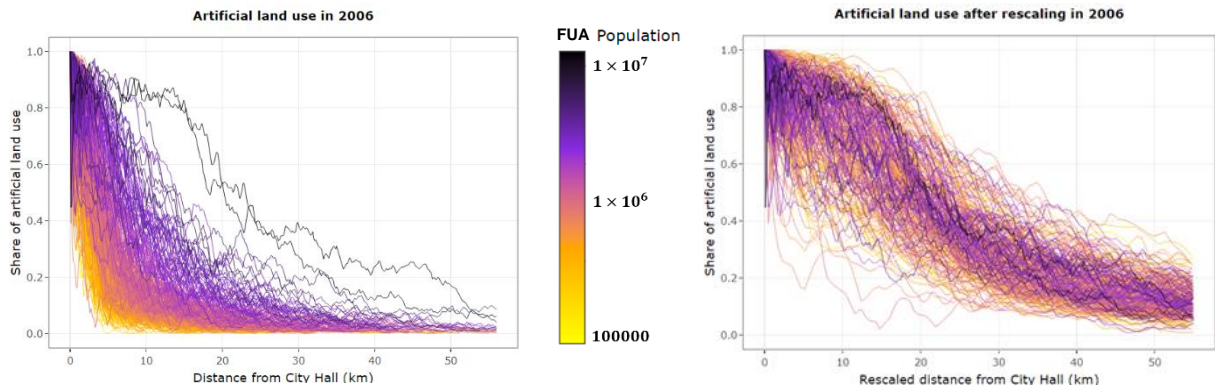


Figure 1. Radial profiles of artificial land use for 305 European cities, raw (on the left) and rescaled (on the right)

Applied to our database, we notice that the infra-urban scaling laws proposed by Lemoy and Caruso (2020) correct for the size effect in the share of artificial land use from the city center (figure 1). For example, the largest cities ( $k = 1$ ) with purple curves and the smallest cities ( $k = 10$ ) with yellow curves exhibit converging and relatively homogeneous radial profiles. This urban scaling law, therefore, captures the effect of city size. The city radius  $r$  scales like the square root of the city population  $N$ , so the artificial area  $\pi r^2$  is proportional to the city population  $N$  ( $r \sim \sqrt{N}$  and  $\pi r^2 \sim N$ )

Thus, the artificial area per capita is constant whatever the city size. The artificial area around the city center scales linearly with the population of the urban area.

These particular points of view to analyze cities are promising for urban planning. This is why geovisualization will be beneficial to make these results more accessible and operational.

### 2.3. Technical part

The web platform was developed using the R Shiny package which is open-source and enables the creation of interactive and intuitive analysis interfaces. This approach allows for broader accessibility through geovisualization (Keim et al., 2008). The objective is to provide a convenient tool for land use planning actors and researchers by transforming the information overload into clear and readable information. The interface was designed to be simple and not have too many distractions to maintain the user's focus and interest (Smith, 2017). The use of the R language was chosen for its statistical and cartographic capabilities.

This web application proposes various tabs that allow the user to interact with the data, understand the methodology, and compare different cities. It is designed to be user-friendly and easy to navigate, with each tab offering specific functionalities. The “Interactive map” tab provides a visual representation of the data, while the “Methodology” tab goes into detail on the urban scaling laws and datasets used. The “European examples” tab provides examples of typical cities with graphs and maps before and after rescaling, while the “Differences on a national scale: France/Spain” tab shows differences in the urban fabric, industries, and roads land use in France and Spain. The “Inter-urban comparison” tab allows the user to compare their city of choice with other cities, with both statistical and cartographic comparisons.

The web application is accessible through a browser and can be found at the following link: [https://land-use.shinyapps.io/UE\\_Land\\_Use\\_2006/](https://land-use.shinyapps.io/UE_Land_Use_2006/). Code and data can also be downloaded with this GitHub link: <https://github.com/axelpec/Urban-Scaling-Laws-2006.git>

### **3. Presentation of the web application**

#### **3.1. Home and methodology tab**

The interactive map, as shown in Figure 2, offers a comprehensive perspective of European cities’ sizes in relation to their artificial land use. Each city is represented by a circle on the map, the size of which is indicative of the average proportion of artificial land use, comparable to a disc encompassing London. The size of these circles is adjusted by the user-selected distance from the city center (which can range between 5 and 100 km). The radius  $R$  of each disc is determined by dividing the chosen distance  $D_{Chosen}$  by the city-specific rescaling factor  $k$ :

$$R = \frac{D_{Chosen}}{k}$$

*Equation 3. The equation to obtain the radius of each city's discs as a function of the scaling factor  $k$*



This map lays the foundation for further analysis and comparison. This home map (figure 2) is interactive: the display can be modified (zoom, translate), the base map can be chosen between satellite view (day) and night lights. With the night light base map, the visualization is strongly reminiscent of the relationship found by Tobler (Tobler, 1969). Indeed, Tobler states that the built-up area of an agglomeration is proportional to the population with an exponent of 0.44 for the radius scale (Tobler, 1969 - “Figure 2: Comparison of actual towns and theoretically calculated towns”). It is quite close to the exponent 0.5 used for the results presented in this application. With the increased availability of data and more powerful technical means, it is now possible to verify these claims and results, as with this map.



Other interactive features include the possibility to load additional layers such as the French local administrative units "Etablissements Publics de Coopération Intercommunale" (EPCIs) and European Functional urban areas (FUAs) for a comparison, and access information on the rescaling factor, radius equivalence, and share of artificial land use for each city. Overall, the application offers a new look at European cities thanks to the rescaling of the issue of artificial land use.

The methodology section provides a concise overview of the subject matter, defining key terms and graphically illustrating the operation of urban scaling laws. It also features an animated GIF demonstrating that the optimal exponent for the calculation of rescaling factors, with respect to the total population ( $N$ ), is 0.5, equating to the square root of  $N$  ( $\sqrt{N}$ ).

*Figure 2. Size of cities according to their artificial land use – London is taken as a reference and by a disc with a radius of 50 km*

Specifically, when the exponent is less than 0.5, smaller cities fall below larger ones (Figure 1 shows that without a change of scale, i.e. at exponent 0, the small towns with the yellow curves are really below the large towns with the purple curves). If the exponent is greater than 0.5, they rise above larger cities. When the exponent is 0.5, the smallest and largest cities align, thereby resulting in the highest observable regularity, as can be discerned in Figure 1.

### 3.2. European examples

The “European examples” tab of the web application is dedicated to visualizing the rescaling of four cities of different sizes: Paris (with a population,  $N$ , of 11,441,532), Madrid ( $N = 5,965,816$ ), Bucharest ( $N = 2,133,066$ ), and Innsbruck ( $N = 276,003$ ). This tab aims to illustrate the impact of urban scaling on the spatial layout of these cities, achieved by examining their radial distances from the city center (the difference in the radius from the city center for these four cities is shown in Figure 3).

For illustrative purposes, consider Madrid, where we employ a rescaling factor of 1.421 ( $\sqrt{\frac{N_{London}}{N_{Madrid}}} = 1.421$ ). This implies that similar levels of artificial land can be found at 30 km of London's city hall and at 21.1 km of Madrid's city hall (calculated by  $30/1.421 = 21.1$ ). To put it simply, this rescaling factor of 1.421 means that the distances from the center of London must be divided by 1.421 in order to compare with distances in Madrid's area.

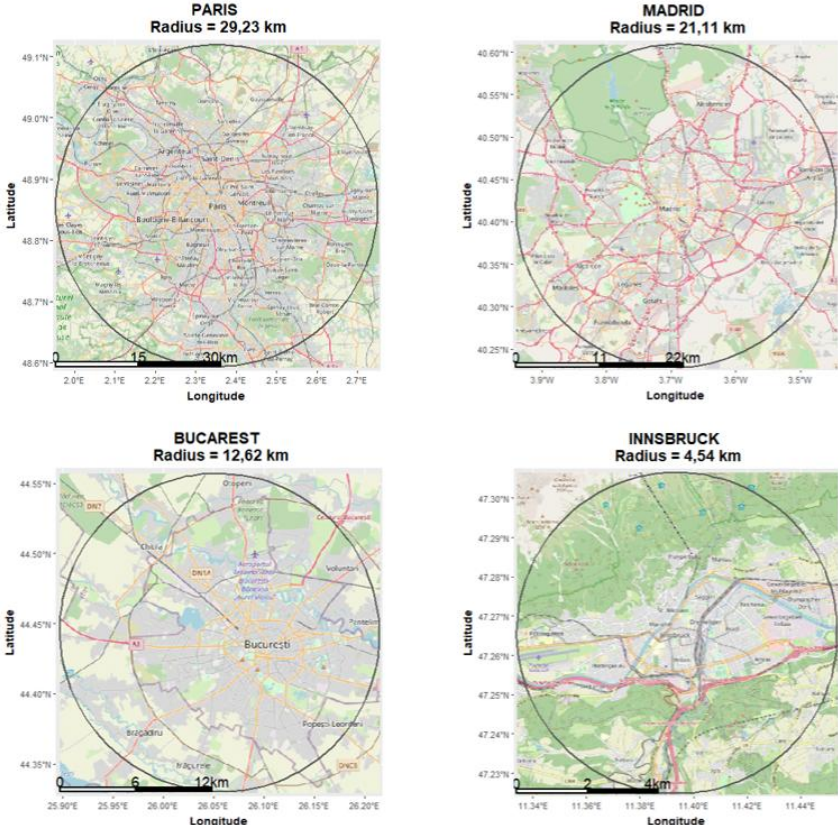


Figure 3. Visual comparison of rescaled discs 30 km radius for London

The synthetic graph (figure 4) shows that cities have a regular organization in their radial succession of land uses. For 80% of the database, the deviation in the share of land use change is at most 0.4 for the 300 largest European cities, on the whole radial profile. The fluctuations around the average are quite limited and are evenly distributed when comparing positive and negative deviations.

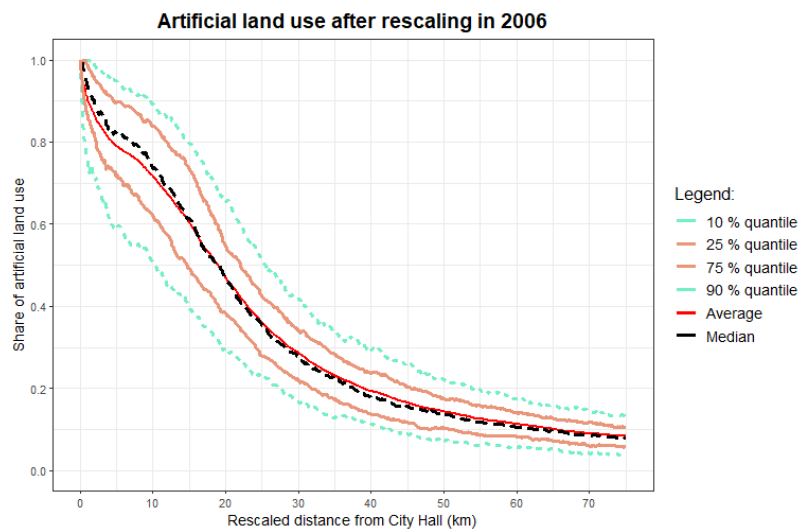


Figure 4. Synthetic representation of artificial land use profiles after rescaling in 2006

### 3.3. Differences in artificial land use on a national scale: France/Spain case study

Urban scaling laws give precise ideas about general trends. However, some cities diverge from the general trend identified using scaling laws, and marginal variations become apparent. In particular regarding land use, two large countries stand out compared to the average European city: French cities are more artificial than the average while Spanish cities are less (figure 5), more specifically in the first 10-40 kilometers (rescaled distance with London as reference). It is therefore interesting to study the differences in artificial land uses and to analyze which types of artificial areas can be found in excess in France.

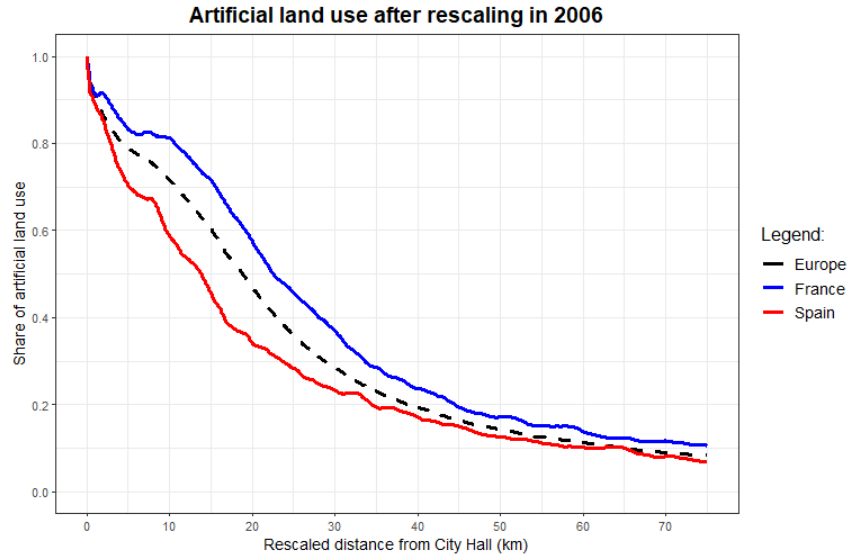
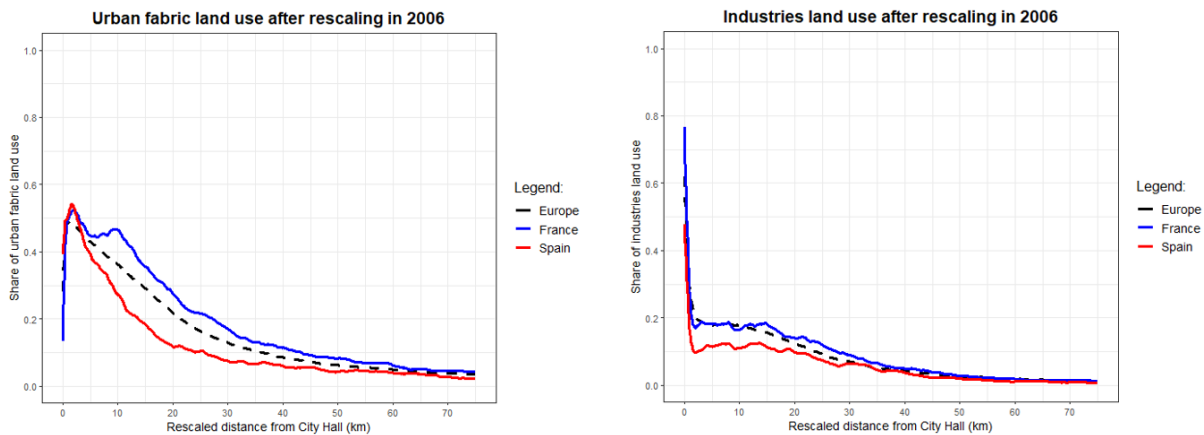


Figure 5. Artificial land use profiles after rescaling in France and Spain, in 2006

The disparity in artificial land use between France and Spain is primarily driven by the proportion of urban fabric (figure 6). After rescaling, on average, 65.4% of the difference in



land use between France and Spain is due to urban fabric. In terms of land used for industries (incorporating “industrial, commercial, public, military and private units”), the difference between the two countries is equivalent to an average of 30.5%. The difference in road land use between France and Spain is relatively small, even though France has slightly higher proportions. This can be attributed to the higher proportions of urban fabric and industrial land use in France (figure 6). In addition, the average number of people per household in France in 2006 was 2.3, compared with 2.7 in Spain<sup>2</sup>. There is therefore a 15% difference between the two countries, which may be one of the reasons why the proportion of urban fabric in France is higher.

<sup>2</sup> [https://ec.europa.eu/eurostat/databrowser/view/ILC\\_LVPH01\\_custom\\_2060213/default/table?lang=fr](https://ec.europa.eu/eurostat/databrowser/view/ILC_LVPH01_custom_2060213/default/table?lang=fr)

The variations observed in artificial land use between French and Spanish cities can also be attributed to a combination of topographical, historical, cultural, and planning factors. Spanish cities are characterized by more small compact clusters of urban areas (Laborde, 1984) surrounded by agricultural lands, while in France, there is a greater presence of low-density peri-urban areas after controlling for size effects through rescaling. During the period of dictatorship and autarky (1939-1959), Spain was submitted to an international trade embargo, which severely limited economic performance and urban expansion (Eduard et al., 2019).

*Figure 6. Urban fabric and industries land use profiles, after rescaling, in France and Spain in 2006*

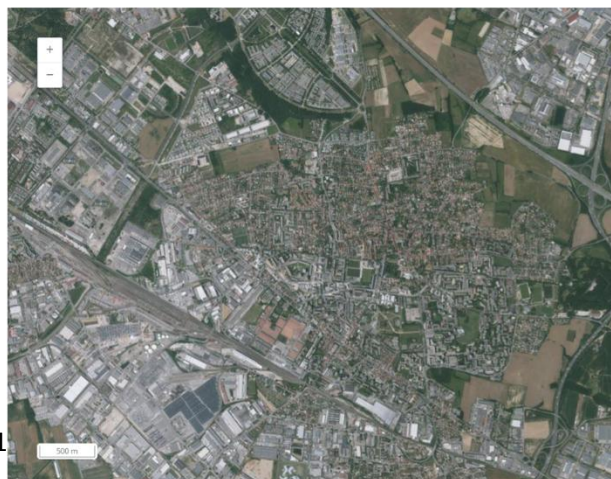
Moreover, in Spain, until 1960, urban development choices were made to use the land already available within cities and the construction of high buildings, which may explain why Spanish cities are more compact due to the existence of consolidated historical centers (Chueca, 1968). Then, to cope with the arrival of new city dwellers, satellite cities were built near major metropolitan areas (Diaz, 2007). One should also note that the climate of the region can play a role in the concentration of urban areas, with warm and dry regions typically having a higher concentration of buildings (Fernando et al., 2016).

In comparison, in France, the urban expansion and fragmentation were primarily driven by slow industrialization, which was unevenly distributed across the country. Additionally, another difference with Spain is the great spread of social housing and "grands ensembles" in the 1960s. The successive strata of suburbs, suburban areas, and new suburban villages with a large number of commercial areas around them (Figure 7) have become the living environment of a majority of French people (Fourcaut, 2003). These differences in urban contexts and planning policies can explain why French cities have more artificial land use than Spanish cities.

**Bormujos, near Sevilla**



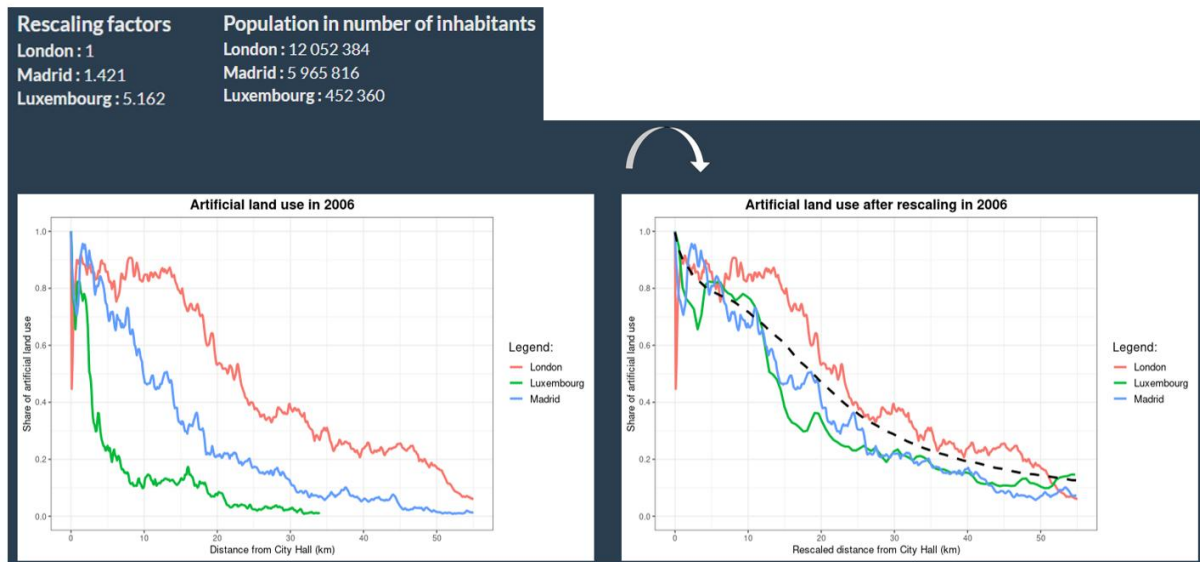
**Saint-Priest, near Lyon**



*Figure 7. Aerial images from 2023 to see the difference between a periurban area in Spain and one in France*  
- Source for Spain: <https://www.qeamap.com/fr/orthophoto-comparator-espagne#13/42.8056/-0.5182> –  
Source for France: <https://remonterletemps.ign.fr/>

### 3.4. Inter-urban comparison: “And my city, how does it stand?”

By employing the application to statistically and cartographically assess land use profiles across European cities, stakeholders, including urban planners and policymakers, can effectively benchmark a city against others in the database. This approach goes beyond mere population size comparisons, offering a fresh lens on urban areas. The European average, depicted by a dotted black line (Figure 8), stands as an additional reference point. Comparisons can be made on criteria other than city size alone, but on artificial land use



profiles.

Figure 8. User-defined selection to visualize artificial land use profiles in 2006

This tab serves a critical function beyond merely graphically comparing cities. Its design aids users in dissecting the urban fabric by quantitatively displaying the distribution of artificial land, divided into categories like urban fabric, industrial use, and roads. Visualized data effectively allows stakeholders to pinpoint highly artificialized zones within each city (Figure 9). Moreover, by placing individual city profiles alongside the European average, users can derive contextual insights, understanding where a city stands in relation to broader European trends.

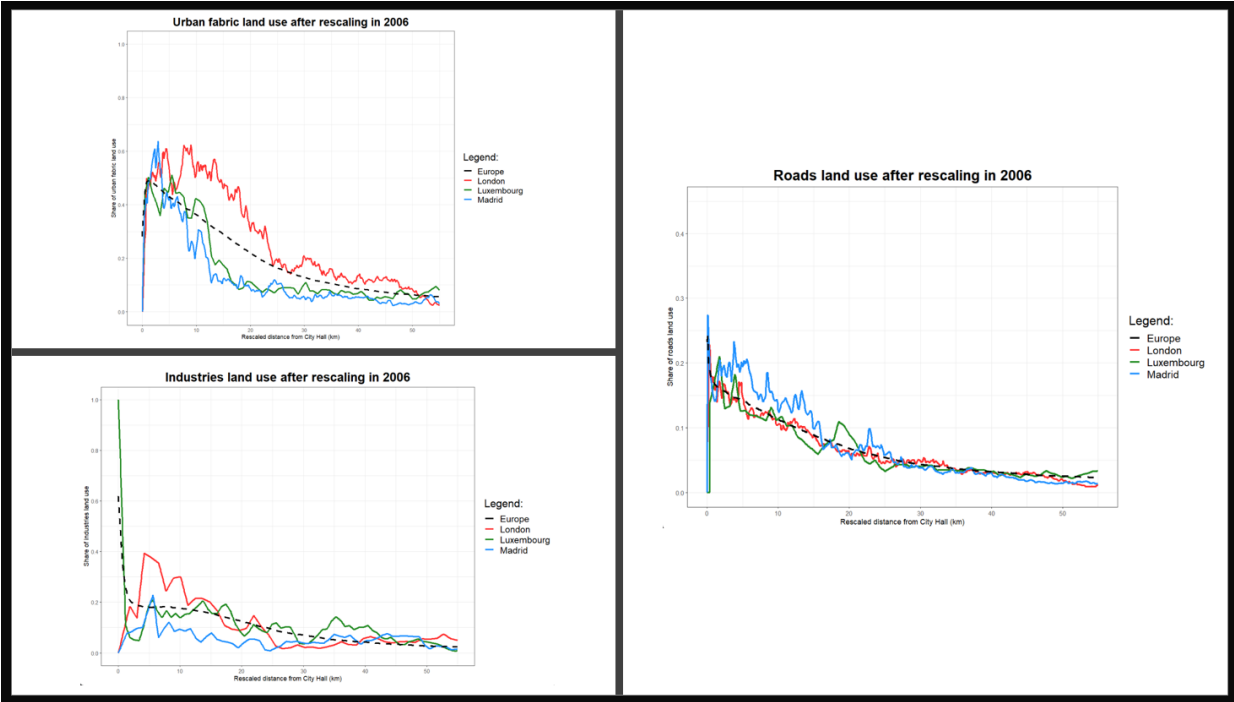
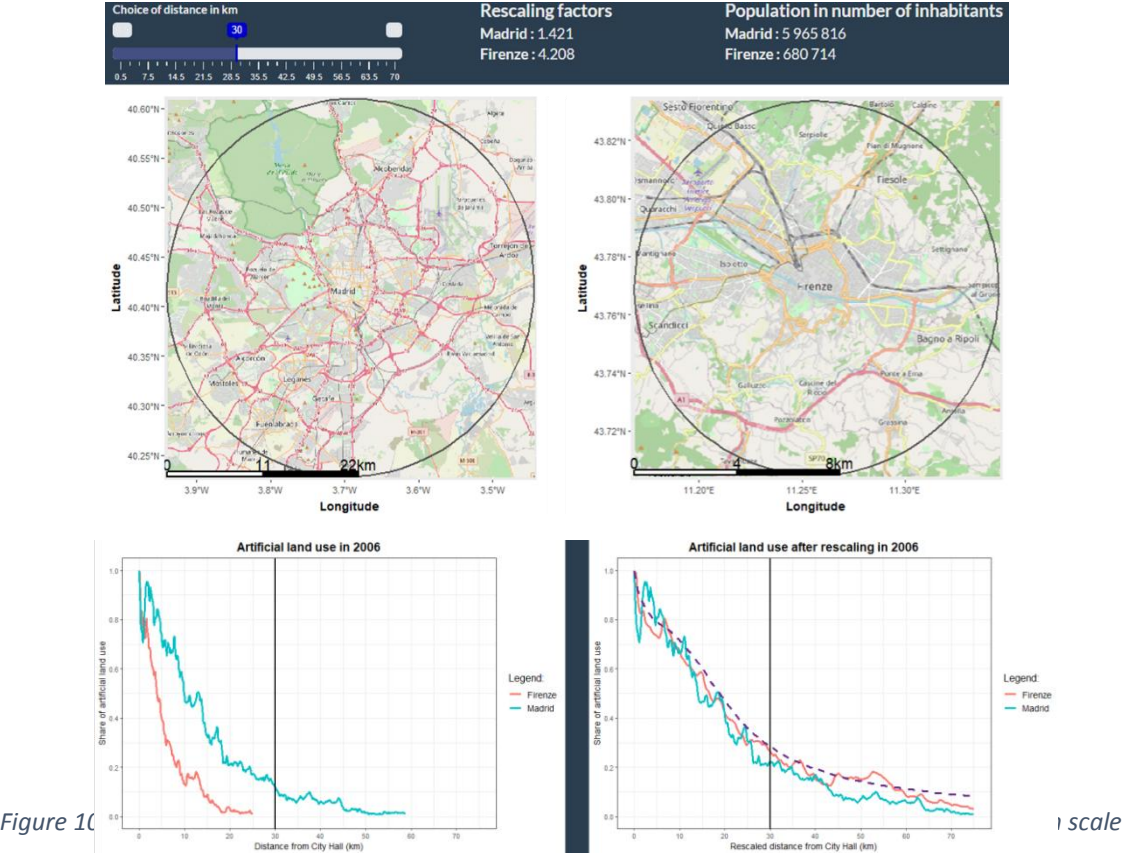


Figure 9. Urban fabric, industries and roads land uses profiles for London, Madrid and Luxembourg in 2006

In our quest to enhance the applicability and usefulness of our research, we have developed an interactive tool that liberates us from the constraints of city size. On this basis, we assess the quantity of artificial land use. This is derived from the radius of the circle chosen by the user, which corresponds to the distance from the city center. As an example, in Figure 10, we choose a distance of 30 km from the center of London (the slider allows the user to select the desired distance and a vertical bar is also shown on the graphs). This is equivalent to a distance of 7.2 km from Florence city center, with an artificial land use share of 26%. This effect is more clearly seen with the scales below the map. In the case of Madrid, this equates to 23% artificial land use at a distance of 21.2 km from its center (equivalent to

30 km from the center of London). It is surprising to see on the maps that there are similar and regular land uses (on maps the effectiveness of the scaling law is less obvious).



Making comparisons with nearby cities or cities of similar size obscures part of the overall understanding. Intriguingly, a city's artificial land use patterns can sometimes resonate more with cities that are geographically distant and have varying population metrics. Our application's insights underline this perspective shift, highlighting that cities can indeed find parallelisms beyond their immediate region or size. For example, an exploration between Firenze and other geographically distant European cities reveals shared radial patterns of artificial land use, irrespective of their population size. Such findings underscore the potential for diversified benchmarking in urban planning, emphasizing that cities can draw valuable insights from counterparts of different scales. It also raises curiosity about the strategic urban planning strategies employed across different cities. Moreover, it is worth investigating why specific urban development projects prove to be more effective in some cities than others (Cusin and Damon, 2010).



The practice of benchmarking, or drawing comparisons between one's city and others that have proven successful in some aspects, is a common strategy among urban planning practitioners (Dash and Balachandra, 2016; Blain et al., 2021). In the application's final tab, a visualization tool presents the European cities showing the most substantial resemblance in terms of their land use profiles. This comparison is relative to the city selected by the user, as demonstrated in Figure 11. The Pearson's correlation coefficient is employed to gauge the degree of correlation and similarity between selected cities. This coefficient calculation features in a correlation matrix that includes all cities, integrating values taken at 100-meter intervals from 0 to 100 km. For enhanced user interactivity, the correlation percentage can be adjusted using a slider, offering an advanced degree of flexibility.

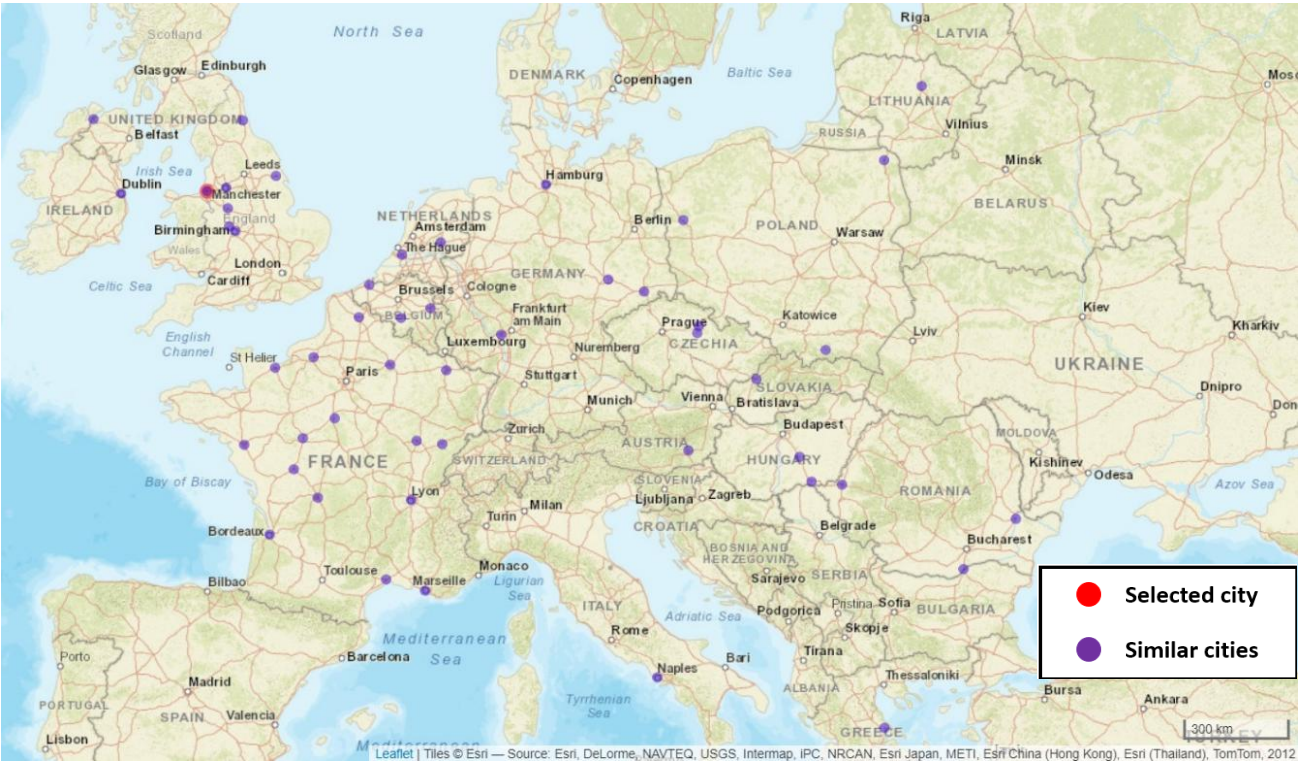


Figure 11. European cities with at least 95% similarity (correlation > 0.95) in their land use profiles to Liverpool's profile

## 4. Discussion of results and conclusions

In general, European cities exhibit a homothetic relationship in terms of radial artificial land use profiles (Lemoy and Caruso, 2020). After rescaling distances to the city hall, we observe a surprising homogeneity of land use patterns across Europe, as seen in the "And my city, how does it stand?" tab where the user can view rescaled land use profiles for selected cities. The common radial structure of European cities features a heterogeneous distribution of people and activities within the urban area, as evidenced by the land use curves for urban fabric, industry, and roads.

To our knowledge, this application is the first to provide a visual representation of a spatial (or morphological) urban scaling law. With a large corpus of cities for analysis and the aim of facilitating comparisons on a European scale, urban scaling laws are an indispensable tool. They enable comparisons irrespective of city size by permitting aggregation on a common basis, thereby fostering a more comprehensive understanding of urban land use patterns and structures.

Today, urban scaling laws primarily yield academic findings that are inadequately translated into practical applications. For instance, these laws could facilitate the identification of effective and ineffective planning practices at national and European levels. Simultaneously, they may reveal alternative, environmentally sustainable urban development and planning approaches that consume less space. Addressing the challenge of urban sprawl requires a combination of densification, requalification of built-up areas, and stringent land control measures. Urban policy does indeed face a major challenge in terms of artificial land use (EEA, 2006).

In response to the pressing need for a more sustainable approach to land management, examining the potential for a large transformation in practices is crucial. Such a paradigm shift would require an effort, engaging governments, urban planners, local communities, and private entities. Adopting evidence-informed strategies, derived from cross-disciplinary research makes promoting sustainable land use patterns possible. These could encompass the integration of green infrastructure, the conservation of agricultural land and natural habitats, as well as advocating for compact urban development. Additionally, raising public awareness and fostering active participation in sustainable land management practices can catalyze a broader societal change, ultimately mitigating adverse environmental consequences and bolstering resilience in the face of future challenges.

Moreover, cities often lack the means to evaluate their degree of urban sprawl. To address this, the European Commission notes that “ideally, cities should be able not only to assess their own situation, but also to compare themselves with other cities”<sup>3</sup>. The web app presented in this paper aligns with this idea and currently serves this role for the year 2006. This web app can be considered as a diagnostic tool in line with the European Commission's ambition to achieve zero net land artificialization by 2050, at the European Union level. In other words, each newly artificialized land will have to be compensated by a "renaturation" of unused artificial spaces.

Using land use profiles provided by this web application, we can identify the most convincing densification zones. For instance, when the population of a city increases, it would be preferable not to densify all areas to the same degree. Conversely, the tool can pinpoint areas where the continuation of urban sprawl could be a more acceptable approach. In essence, the application allows for a more nuanced and site-specific approach to urban planning, moving beyond the simplistic dichotomy of densification versus sprawl. It provides a data-informed foundation upon which future cities can be more effectively planned and managed.

Although urban contexts and planning policies vary, the objective of further work should be to comprehend the factors contributing to the homogeneity of artificial land use patterns in European cities when distances are rescaled (Li et al., 2021). For instance, taking the case of France and Spain, it is likely that cultural variations and variations in household structures contribute to significant differences in the urban form. In order to achieve more informed and holistic urban planning strategies, it is essential to study in greater depth the impact of public policy intervention on urban forms, and to understand what explains these variations between cities.

This web application has significant development potential. Urban scaling laws can be extended beyond land use to encompass environmental or socio-economic outcomes, as well as crucial urban planning aspects such as housing prices, population density, commuting patterns, and building height. Moreover, it can be enriched by adding data at different dates and tools to visualize temporal evolutions and urban sprawl. Our empirical analysis with a temporal perspective could offer insights into urban growth and even suggest predictions

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<sup>3</sup> Commission européenne, Direction générale de la politique régionale et urbaine (2012) Les villes de demain : défis, visions et perspectives. *Publications Office*.

about future developments. Worldwide data will also allow more extensive comparisons between cities.

To conclude, visualization tools can serve to operationalize scaling laws for city management and comparison. Urban scaling laws may be used in the future for areas other than land use, such as for the comparison of environmental or socio-economic outcomes of cities, which are essential for urban planning.

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## **Software**

This web application is developed using the Shiny package of R, and base maps without copyright restrictions. The data source used is the 2006 Copernicus Urban Atlas database with a 5 meter resolution for land use and the 2006 Geostat population grid with a 1 km resolution. Both R and Microsoft Excel are used for organizing and managing the data efficiently.

## **Disclosure statement**

No potential conflict of interest was reported by the authors.

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## Figures and equations captions

**Figure 1.** Radial profiles of artificial land use for 305 European cities, raw (on the left) and rescaled (on the right)

**Figure 2.** Size of cities according to their artificial land use – London is taken as a reference and represented by a disc with a radius of 50 km

**Figure 3.** Visual comparison of rescaled discs 30 km radius for London

**Figure 4.** Synthetic representation of artificial land use profiles after rescaling in 2006

**Figure 5.** Artificial land use profiles after rescaling in France and Spain, in 2006

**Figure 6.** Urban fabric and industries land use profiles, after rescaling, in France and Spain in 2006

**Figure 7.** Aerial images from 2023 to see the difference between a periurban area in Spain and one in France - Source for Spain: <https://www.geamap.com/fr/orthophoto-comparator-espagne#13/42.8056/-0.5182> - Source for France: <https://remonterletemps.ign.fr/>

**Figure 8.** User-defined selection to visualize artificial land use profiles in 2006

**Figure 9.** Urban fabric, industries, and roads land uses profiles for London, Madrid, and Luxembourg in 2006

**Figure 10.** Comparison of artificial land use profiles for Madrid and Florence - 30 km on the London scale

**Figure 11.** European cities with at least 95% similarity (correlation  $> 0.95$ ) in their land use profiles to Liverpool's profile