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Discontinuous structure of regional and subregional urban systems: Nouvelle-Aquitaine, France (1800–2015)

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Abstract

In the prevailing literature in urban economics, conducting research on urban systems at the national scale tends to provide an elegant but reductive approach to the functioning of these systems, assuming, in particular, that city size distributions are continuous. Based on an alternative framework drawing from research in ecology and complex adaptive systems, this article questions this approach by testing the discontinuity hypothesis within regional urban systems in France using two methods and long-term census data (1800–2015). We found that the distribution of city sizes over the 200 + years of population data from the Nouvelle-Aquitaine region was discontinuous for every year of data. The distributions consist of groups of similarly sized cities, separated by gaps (discontinuities) where there are no cities at all. The location and number of discontinuities were conservative over time, suggesting that the processes shaping size classes are conservative and largely independent of societal disturbances such as wars. The two methods used to identify discontinuities were highly congruent. Finally, the Nouvelle-Aquitaine region is comprised of three former regions, Aquitaine, Limousin and Poitou-Charentes, each of which also had discontinuous city size distributions with conservative structures over time. The study results question the traditional expectations about the growth and development of urban systems.

Keywords

agglomeration, city size distribution, demographics, method, urbanisation, urban systems

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摘要
城市经济学的主流文献表明，在全国范围内对城市系统进行研究，往往会为这些系统的运转提供一种简练且简化的方法，尤其是在连续的城市规模分布的情况下。基于一个来源于生态学和复杂的适应系统研究的替代框架，本文通过使用两种方法和长期人口普查数据（1800-2015年）测试法国区域城市系统内的不连续性假设，从而对这种方法提出质疑。我们发现，新阿基坦（Nouvelle-Aquitaine）地区200多年人口数据中的城市规模分布每年都是不连续的。分布图由规模相近的城市组成的群构成，由完全没有城市的缺口（不连续处）分隔。随着时间的推移，不连续处的位置和数量是保守的，这表明影响规模等级的进程是保守的，并且在很大程度上独立于社会干扰，如战争。用于识别不连续处的两种方法高度一致。最后，新阿基坦地区由以前的三个地区组成，即阿基坦（Aquitaine）、利穆赞（Limousin）和普瓦图-夏朗德（Poitou-Charente），一段时间后，每个地区的城市规模分布也变得不连续，结构较为保守。研究结果对城市体系增长和发展的传统期望提出了质疑。

关键词
聚居地、城市规模分布、人口统计学、方法、城市化、城市体系

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Introduction

In the prevailing literature in urban economics, research on urban systems at the national scale tends to assume that city size distributions are continuous because the distributions broadly fit a power law (Gabaix, 1999). However, this perspective does not correspond to an alternative view, which suggests that a power law fit can also mask discontinuities within the distribution (Bessey, 2002; Garmestani et al., 2008). In this paper, we present an alternative framework drawn from research in ecology and complex adaptive systems (CASs) and test whether city size distributions within regional urban systems in France exhibit discontinuities (Holling, 1992). We use two different methods and long-term census data (1800–2015) to evaluate whether the distributions are discontinuous, and whether that discontinuous structure is robust over time.

The fundamental premise of discontinuity theory is that there are 'specific spatio-temporal windows within which pattern and process are tightly coupled relative to the other scales of the system, reflected in the discontinuous distribution of pattern when compared across scales of analysis' (Barichievy et al., 2018: 9615). For instance, numerous ecological studies testing the discontinuity hypothesis have demonstrated that animal body mass size distributions are discontinuous. A species' long-term persistence corresponds to its ability to utilise available resources which occur at distinct spatial and temporal scales, and therefore size corresponds to the available scales of structure such as habitat and food resources (Allen and Holling, 2008; Haskell et al., 2002; Nash et al., 2013). The discontinuity hypothesis has since been expanded to CASs generally (e.g. urban systems, economic systems), as discontinuous distributions are understood to be a signature of multi-scaled processes in CASs (Stow et al., 2007). Like animal body mass distributions, we test whether regional city size distributions are discontinuous, revealing groups of cities with a similar size, separated by gaps or discontinuities in the size distribution. This introduction first reviews the literature on the organisation of urban systems and city size distributions, then explains the discontinuity hypothesis and its relevance to urban economics and closes by explaining the objectives of this paper.

The prevailing paradigm in urban economics is that city size distributions converge towards a Pareto's law (Zipf's law) as a stationary state generated by random urban growth with constant variance (Gibrat's law). Berry and Okulicz-Kozaryn (2011) argue that studies on urban systems in urban economics and regional science are organised around two major streams that question (1) whether city size distributions follow this Pareto law or a lognormal distribution and (2) whether urban growth conforms to Gibrat's law. A third noteworthy axis of research has developed in recent years exploring the principle of scale invariance (Gabaix, 1999) according to which if Zipf's law and Gibrat's law hold at the national level, then both should also hold for each sufficiently large subset of cities, such as regions.

The main debate concerning which probability 'law' best describes city size distributions revolves around whether researchers use part of or the entire distribution, and where they choose to truncate the data set, as these choices directly impact the power law fit. While Eeckhout (2004) investigated the size distribution over the entire range of cities in the United States and found that the empirical data fit to a lognormal distribution, Levy (2009) and Ioannides and Skouras (2009) concluded that the bottom and middle of the empirical distribution of cities fit the lognormal distribution and the top range a power law. Giesen et al. (2010) suggested that a double Pareto lognormal fits better, as the lower and upper tail followed a Pareto distribution, and the mid-ranges were best fit to a lognormal distribution.

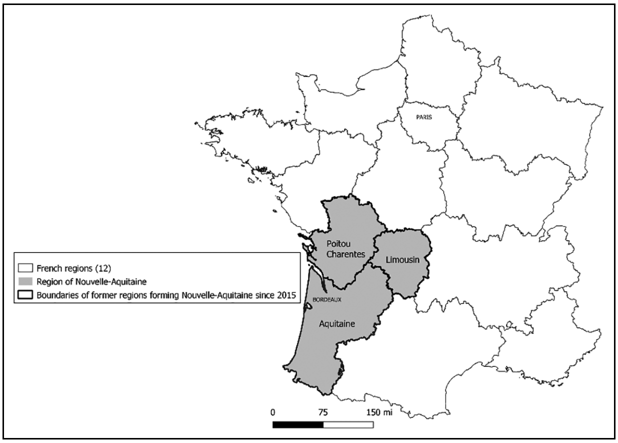
The literature on Gibrat's law has provided contrasting results that may be due to the numerous methods (parametric/non-parametric, panel/cross-section/time-series) and data used for the different areas of research on Gibrat (see Gonzalez-Val et al., 2014). Black and Henderson (2003) used a panel unit-root test and rejected random growth of US cities, whereas Gabaix and Ioannides (2004) and Gonzalez-Val et al. (2014) used a kernel density estimation on the same country and found random growth. For non-US empirical studies, Soo (2007) used Malaysian census data (1957–2000) and parametric methods and rejected random urban growth. From data on French cities' population covering almost two centuries (1836–1990), Guerin-Pace (1995) rejected random growth based on a parametric approach. Finally, while Lalanne and Zumpe[1] (2020) confirmed that French cities observe random growth through a unit-root test, Lalanne and Zumpe (2019) also demonstrated that random growth processes can be very diverse (three processes at least) and that Gibrat's law is not the only stochastic process operating in urban systems. Nonetheless, departures from Zipf's and Gibrat's laws constitute exciting research perspectives and have been documented in the literature on urban economics by, for example, natural advantage locations or industrial composition among other things (Gabaix and Ioannides, 2004). In particular, Davis and Weinstein (2002) interpreted the persistence of Japan's urban system after WWII as evidence against random growth and in favour of the locational fundamentals theory.

A third axis of work has developed which applies these questions to regional rather than national scales and questions the principle of scale invariance developed by Gabaix (1999). According to the principle of scale invariance, Zipf's and Gibrat's laws observed at the national level should be valid for all regional-level subsystems. Regional specificities have received less attention in the scientific literature but studies on the principle of scale invariance are the starting point for increased attention given to regional system structures (Garmestani et al., 2005, 2007). Giesen and Südekum (2011) addressed the validity of Gibrat's law at a regional scale and observed that Zipf's law was upheld for all German regions. They observed that urban growth at the top of the distribution is consistent with the scale invariance principle for the three types of regions they defined. However, Garmestani et al. (2007) observed departures from Gibrat's law in the south-eastern region of the US, as did Lalanne (2021) for the south-west region of France.

Here, we borrow theory from ecology and complex systems science, which consider urban systems as CASs that form hierarchical structures at different scales (i.e. have a multitude of equilibria; Gunderson and Holling, 2002). Consequently, in this paper we do not seek to determine the 'law of the city size distribution', nor do we seek to confirm/infirm Gibrat's law. Rather, we draw from complex systems theory that views system structure, such as a size distribution, from the perspective of hierarchy and scaling processes (Holling, 1992; Schneider and Kay, 1994), from which flows the hypothesis that city size distributions, including regional distributions, may be discontinuous.

The linearity and continuity depicted at aggregate national scales may actually obscure variation observed in a multi-scale regional analysis (Bessey, 2002). A number of studies already reveal regional diversities and break with the view that urban systems are scale invariant. Lalanne (2014) has shown that a national urban system, such as Canada, can be governed by different growth processes, making it difficult to validate the two laws. In an analysis of regional city size distributions that examined Zipf's law, which predicts that city size distributions will be continuous and fit a linear power law, Garmestani et al. (2008) demonstrated that the power law fit provided a poor fit in the tails of city size distributions, and that in fact different power laws fit over different ranges of scale. In other words, the city size distribution was discontinuous, and was best explained as a series of power law fits, where one power law fit over a range of scales represented by a group of similarly sized cities, while the next group of cities was best fit by a different power law. The findings in Garmestani et al. (2005, 2007), however, remain the only urban subsystems for which empirical evidence of the discontinuity hypothesis has been established, leaving an open question as to whether discontinuous structuring of urban systems is a general property.

CASs, regardless of type, share commonalities stemming from the thermodynamic properties underpinning system behaviour (Schneider and Kay, 1994). One of those commonalities is that CASs are multi-scaled and hierarchical in space and time, with different processes governing different ranges of scale (Gunderson and Holling, 2002). The discontinuity hypothesis posits that because key ecosystem processes occur at distinct and limited ranges of spatial and temporal scales, so too should ecosystem structure (Holling, 1992). Wiens (1989) called these distinct ranges of scale over which processes operate 'scale domains' and defined them as 'regions over which patterns either do not change or change monotonically with changes in scale' (p. 392). The discontinuity hypothesis goes one step further and argues that if processes and structures occur over limited and distinct ranges of scale, then so too should system entities that interact with those processes and structures. In other words, species have body masses that correspond with the spatial and temporal scales at which ecological structure is available—having a body mass that corresponds to available scales of structure such as habitat and food resources will increase evolutionary fitness. Breaks between scale domains are called discontinuities and demarcate sharp changes in dominance from one set of structuring processes to another. More than 30 years of research have confirmed the discontinuity hypothesis in multiple ecosystem types and across multiple taxa and



Map 1. Region Nouvelle-Aquitaine and three former regions (Poitou-Charentes, Limousin and Aquitaine).

timescales (Allen et al., 1999; Allen and Holling, 2008; Holling, 1992; Nash et al., 2014; Spanbauer et al., 2016).

Research extending the discontinuity hypothesis to other CASs (e.g. urban systems) has also demonstrated the highly conservative nature of the location of scale domains and the discontinuities separating them, providing a measurable approach for understanding scales in CASs. For example, an analysis of the world's national economies showed that the size distribution (per capital real GDP) was both discontinuous and conservative (groups and gaps in a similar location over time) for 42 years of data (Sundstrom et al., 2020). Similarly, city sizes in the south-west and south-east regions of the US were discontinuous over 100-year timeframes in both cases, as well as manufacturing firm sizes in South Carolina, US (albeit with a short-term dataset; Garmestani et al., 2005, 2006, 2008), where the size distribution of these entities was defined by size classes, with sharp discontinuities between them. This suggests that the processes that structure these social systems occur at discrete and limited ranges of spatial and temporal scales and that, in turn, this shapes the size of the entities that interact with those structuring processes.

In this article, we test the discontinuity hypothesis on a French regional urban system: Nouvelle-Aquitaine. It is a new region created during the 2015 territorial reform in France, which defines 12 large new regions (compared to 22 previously). Nouvelle-Aquitaine is the largest region with an area equivalent to that of a small country like Austria. With these new borders, this region of south-western France regains its historical boundaries and merges three former regions: Aquitaine, Limousin and Poitou-Charentes (see Map 1). The importance of the regional development policies conducted by the European Union increases the need for knowledge about the functioning of regional urban systems.

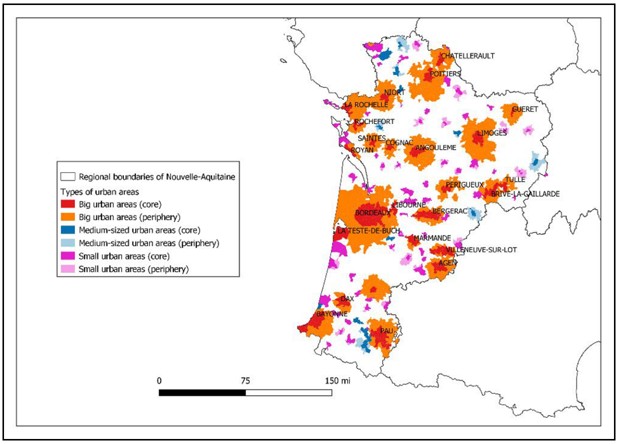
Therefore, this article has three purposes. First, we test whether there are size classes and discontinuities in population census data for the Nouvelle-Aquitaine region of France using long-term data. It is highly probable that the numerous events of the 20th century (e.g. industrial revolution, World Wars I and II) have disrupted the urban hierarchy. Second, we identify whether the location of the size classes and discontinuities is conservative over time. We also test for discontinuous structure in the three old regions that comprise the modern-day region of Nouvelle-Aquitaine (Aquitaine, Limousin and Poitou-Charentes, see Map 1). We will thus be able to observe whether the location of size classes and discontinuities are conservative over time within the three subregions. Third, we compare two methods for identifying discontinuities, the Discontinuity Detector (DD) and the Bayesian Classification and Regression Tree (BCART). The Discontinuity Detector is a newer method (Barichievy et al., 2018) so we compare the two methods for convergence in results.

Data and methods

Our analysis uses census data from French municipalities from 1800 to 1999 from the Cassini database made available online by the School of Advanced Studies in the Social Sciences (EHESS) historical demography laboratory. We completed these data with the most recent censuses from 2006, 2011 and 2015, which are provided by the French National Institute of Statistics and Economic Studies (INSEE). The census was conducted every 5–11 years, resulting in 35 independent data sets for Nouvelle-Aquitaine. We also partitioned the Nouvelle-Aquitaine data by its three former regions (Poitou-Charentes, Limousin and Aquitaine) in order to run the discontinuity analysis on each sub-region, for a total of 140 census datasets spanning >200 years.

A reconstruction of the municipalities' perimeter was necessary to ensure a consistent comparison over the entire period. The boundaries of some municipalities changed over time due to mergers and separations. We chose the 2015 census boundaries as our baseline perimeters, and each municipality, from the beginning of the time series to the end, is defined according to these perimeters. This harmonisation of perimeters makes it possible (1) to make the municipalities comparable with each other over the entire period, (2) to eliminate the effects of artificial growth linked to a merger of municipalities and (3) to account for all the municipalities in the study, including those whose census ceases after a merger with another municipality. For example, the municipality of Caudéran merged with the municipality of Bordeaux in 1965. This means that the censuses of Caudéran ceased to exist from this date and were directly integrated into those of Bordeaux. Thus, to be able to compare Bordeaux before and after 1965 and not capture an artificial growth only linked to this merger, it is necessary to integrate Caudéran into Bordeaux over the entire time series. In addition, this makes it possible to include Caudéran in the analysis, which could not be exploited with the disappearance of its censuses from 1965 on. After standardising and reconstructing the municipalities' perimeters, the municipalities were aggregated into urban areas that represent a unified labour market. Urban areas are the suitable level of organisation with which to measure discontinuities because they correspond to a functional definition of cities (Bessey, 2002). Urban areas are a group of contiguous municipalities connected by employment ties and are comprised of an urban centre and its periphery, whereby at least 40% of the residents in the periphery work in the centre.

As this was a systems analysis, we chose to study the whole distribution from the largest to smallest urban area. In Nouvelle-Aquitaine, there are 106 urban areas that cover 75.15% of the regional population (Map 2, 25 large urban areas in red and orange; 13 medium urban areas in dark and light blue; and 68 small urban areas in dark and light pink). The size of the largest urban areas increases significantly over time, while the median size only increases minimally



Map 2. Urban areas in Nouvelle-Aquitaine.

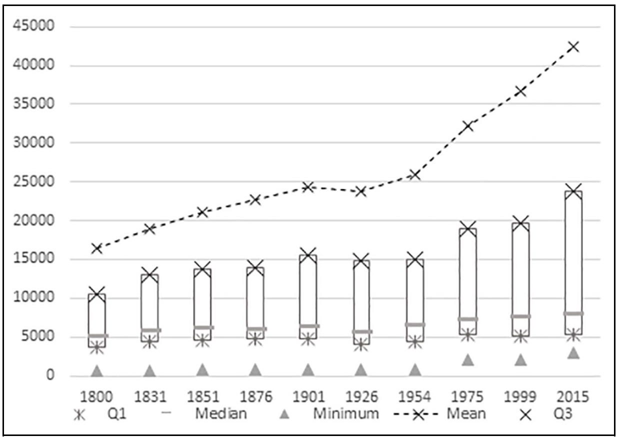


Figure 1. Box-plot of the population of Nouvelle-Aquitaine (*y*-axis) by year (*x*-axis).
The maximum is not shown because of its high value.

over the 200 years of data (Figure 1). After partitioning Nouvelle-Aquitaine into its three former regions, there were 35 urban areas for Poitou-Charentes, 15 for Limousin and 56 for Aquitaine. In the case of Limousin, the number of urban areas is small so the results must therefore be interpreted with caution.

All years of data were log-transformed, and each rank-ordered distribution was analysed for discontinuities. Methods to detect discontinuities in rank-ordered size data have evolved since they were first applied by Holling (1992). Early efforts used a split moving window difference index to identify larger-than-expected gaps and then confirmed results with hierarchical cluster analysis (Holling, 1992). Restrepo et al. (1997) introduced the Gap Rarity Index (GRI), which compares a continuous unimodal null distribution generated by smoothing the observed data with a kernel density estimator to the observed size distribution. The GRI was recently modified to improve its methodological transparency (Barichievy et al., 2018), and the refined method is called the Discontinuity Detector (DD). A Bayesian implementation of a Classification and Regression Tree (BCART) has also been heavily utilised. This method performs a stochastic search over the space of all possible trees, using prior probabilities of a split occurring at any given node while the log integrated likelihood is used to select the best tree (Breiman et al., 1984; Chipman et al., 1998).

The results from the aforementioned methods have been shown to be highly congruent, though not identical (Stow et al., 2007). Since every method has biases, the recommended best practice for the detection of discontinuities has been the use of multiple methods to assess for convergence in results (Holling and Allen, 2002; Stow et al., 2007). To that end, we used the BCART and DD on all years of all data sets and compared the results. The BCART is minimally sensitive to selection of prior probability, but the number of iterations is important, so we followed standard procedure and used a fixed prior of 0.5 and ran 1 million iterations 25 times (Stow et al., 2007). An aggregation was defined as a minimum of three or more cities separated by a discontinuity unless the city fell at either end of the distribution, in which case it was considered to be an aggregation by itself.

Results

Both methods identified discontinuities in all years of the population census data of Nouvelle-Aquitaine and its three subregions. Results across the two methods were virtually identical, with the significant difference being that the BCART was more conservative—it identified fewer discontinuities in the data. In general, the BCART and DD identified gaps in the same location for each year of the census data, but the DD tended to parse the rank-ordered data more finely (Figure 2). The congruence in results confirms the likelihood that the gaps represent a non-random pattern in the distributions. We choose to present only the BCART results throughout the rest of the paper, as they are the more conservative results.

The results confirm the hypothesis that the distribution of city sizes in the Nouvelle-Aquitaine region is discontinuous and also that these discontinuities are relatively stable in terms of the number of groups over the entire period studied, as well as the location of the groups and discontinuities (Figure 3). The number of groups is constant over a century (10 groups between 1800 and 1900) and then varies between eight and 11 during the 20th century with a trend towards fewer groups over time (Figure 4). Moreover, unsurprisingly, Bordeaux dominates the regional urban system. This city is isolated at the top of the distribution and most of the time forms a group on its own. The relationship between Bordeaux and the next largest city, Limoges, is fairly constant throughout the entire period. Limoges has a population that is ~40% of the size of Bordeaux (39% in 1800 and 37% between 1891 and 1906; see Table 1). Note that according to Zipf's law, the size of the second city should represent 50% of the first one. This ratio is quite stable until the second part of the 20th century, when the ratio decreases and Limoges represents only 26% of the size of Bordeaux in 1999, and then 25% in 2015. The strengthening of a primate urban hierarchy is specific to the phenomenon of globalisation (Pumain and Moriconi-Ebrard, 1997).

Between 1891 and 1926, Bordeaux was not in its own aggregation, but formed a group with Limoges, the largest city of the

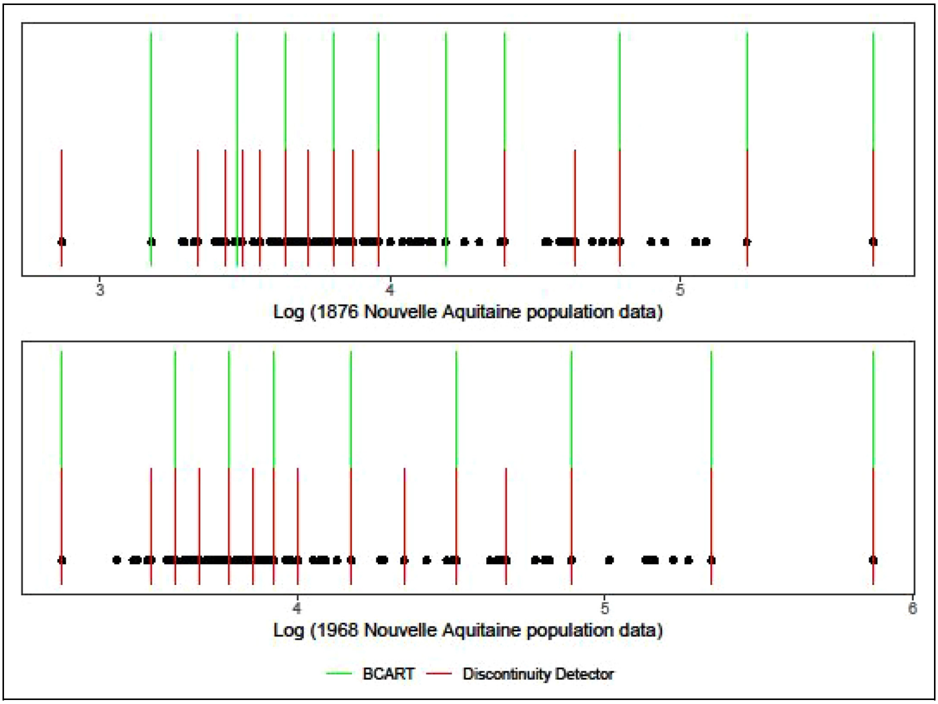


Figure 2. Comparison of two discontinuity-detection methods on log-transformed Nouvelle-Aquitaine census data from 1876 and 1968.

The Bayesian Classification and Regression Tree (BCART; red) and the Discontinuity Detector (DD; green) demonstrate high congruence in the location of discontinuities, though the DD tends to find more gaps.

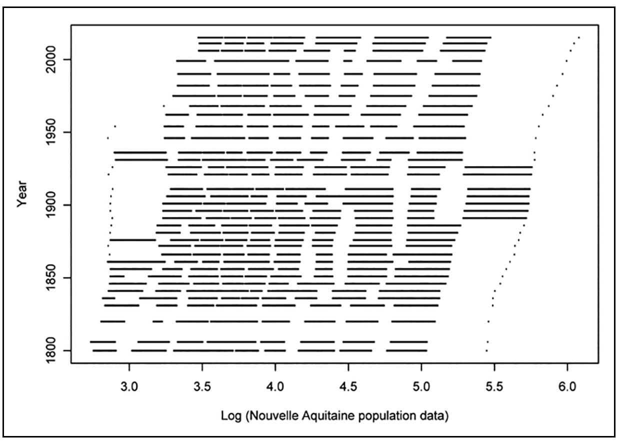


Figure 3. The discontinuous distribution of log-transformed census data from Nouvelle-Aquitaine from 1800 to 2015.

The black polygons represent clusters of similarly-sized urban areas, while gaps represent locations in the distribution where there are no urban areas of that size.

Figure 4. The number of aggregations (size classes) for each year of Nouvelle-Aquitaine census data.

Table 1. Size ratio in the city size distribution (1800–2015).

	1800 (%)	1851 (%)	1891 (%)	1906 (%)	1926 (%)	1999 (%)	2015 (%)
Size ratio between first and second city[a]	39	42	37	37	35	26	25
Size ratio between second and third city[b]	83	78	63	61	72	98	96

[a]Ratio = size of second city/size of first city.
[b]Ratio = size of the third city/size of the second city.

former Limousin region and the second largest city of the new Nouvelle-Aquitaine region for two centuries. At the beginning of this period (1891–1926), the second and third cities are relatively similar in size. In 1800, the size of the third city (Pau) was 83% of the size of the second city. Pau held this third-place position until 1906, when the 8% decrease in its population between 1891 and 1906 caused it to lose its rank. There was a constant decrease in this ratio (between 60% and 63% from 1891 to 1926). The growing gap between Pau and Limoges resulted in Bordeaux and Limoges being in the same group during this period. The ratio between the second and the third cities of the distribution increased again from 1930 to reach the ratio levels of the beginning of the period. Bayonne, with growth of 23% over the same period, moved into the third position in place of Pau and gradually closed the gap with Limoges. Bayonne's coastal location proved very favourable during this period of history as the region experienced a significant development of seaside tourism along the Atlantic coast as early as 1850. Previously, Eason and Garmestani (2012) found that growth rates of cities at a regional scale in the US were correlated to two factors: quality of weather (e.g. sunny days) and amenities (e.g. beaches, parks and museums).

The smallest urban area, Artix, is isolated in an aggregation of its own at the bottom of the distribution from 1906 to 1957. Although it formed a group with Morcenx and Capbreton at the beginning of the time series in 1800, Artix was in its own group from 1906 because the other small urban area such as Capbreton, a coastal city, experienced a demographic boom due to the development of tourism at the beginning of the 20th century. Artix began to grow rapidly in the 1960s with the exploitation of gas deposits in 1957 and the commissioning of the Artix power plant fuelled by natural gas.

The three former regions of Poitou-Charentes, Limousin and Aquitaine also had discontinuous distributions for all years of census data. The Poitou–Charentes regional urban system was particularly stable and homogeneous over two centuries in terms of both the location and number of discontinuities and aggregations (see Figure 5a for the location of discontinuities from 1800 to 1999; there were six discontinuities in every year of the data bar one). The top of the hierarchy was consistently the same four cities (Angoulême, Poitiers, La Rochelle and Niort) which correspond to the four departmental subdivisions of this region. The second aggregation in the distribution (second from the right) was also consistent in its makeup over time, comprising Saintes, Châtellerault, Rochefort and Cognac, with Royan entering this group in the middle of the 19th century. This stability is remarkable considering the events that marked the two centuries. The Limousin region did not show quite as persistent a pattern of discontinuities and aggregations over time, but the results for the former Limousin region are less reliable because the number of urban areas is lower than what is recommended for a discontinuity analysis (Barichievy et al., 2018). Despite the small number of urban areas in that data set, there appears to be relative stability in the organisation of the city size distribution (Figure 5b).

The distribution of city sizes in the former Aquitaine region is also discontinuous (Figure 5c). The largest gap is between the largest urban area in the distribution, and the rest of the distribution. This is typical for a primatial distribution. The Aquitaine region includes the only metropolitan urban area of Nouvelle-Aquitaine, namely, Bordeaux. The rest of the region is composed of very rural territories with much smaller urban areas. Overall, the pattern of discontinuities and aggregations within the three former regions of Nouvelle-Aquitaine and Nouvelle-Aquitaine itself shows a conservative distribution pattern that remains stable over time.

Discussion

This paper tests a basic question about the structure of a regional urban system in France: is the city size distribution discontinuous and are those discontinuities conservative over time? As discussed in the introduction, the structure of the distribution of city sizes has occupied researchers in urban economics and regional science for decades. A dominant part of the literature has focused on a Pareto law organisation. In this paper, we have assessed city size distributions and urban organisation that raises theoretical as well as empirical questions.

Research into discontinuities reflects a fundamental theory about the organisation of CASs, which are hierarchical and multi-scaled as a function of the way systems develop over time (Schneider and Kay, 1994). The discontinuity hypothesis provides a mechanistic explanation for the relationship between the scales of process and structure in a hierarchy, and the size of entities that might interact with that structure (Gunderson and Holling, 2002; Holling,

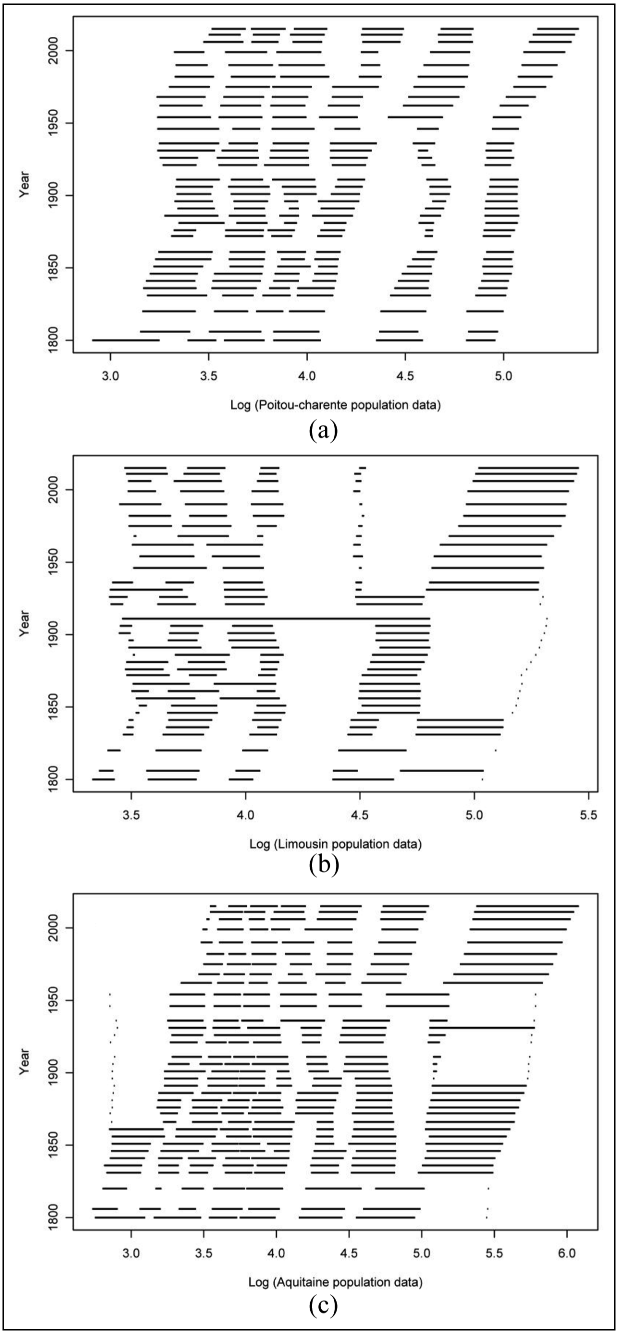


Figure 5. Distributions of log-transformed census data from the three former regions of (a) Poitou–Charentes, (b) Limousin and (c) Aquitaine. Note the *x*-axis is different for each distribution.

1992). Our discontinuity analysis reveals conservative size classes in city size distributions of Nouvelle-Aquitaine and its former subregions. This stable urban structure suggests that urban systems have similar hierarchical and discontinuous structure to other CASs as theorised (Gunderson and Holling, 2002) and as confirmed by prior research on urban systems in the United States (Garmestani et al., 2009). These results are not fully mutually exclusive with a power law fit; indeed, previous research on discontinuities in a regional system has shown that the cities within a size class fit a power law (Garmestani et al., 2008).

The discontinuity hypothesis posits that each size class is structured by a few key processes that operate at that range of spatial and temporal scale. We wish to clarify, however, that the discontinuity analysis merely looks for discontinuities in the distribution—individual cities may in fact move from one size class to another when comparing different years of data. Regardless of the group membership, the size classes themselves are robust over time, which suggests fundamental structuring processes that create domains of opportunity and manifest as a robust hierarchical structure in urban systems. Our results do not preclude the possibility that the size classes are the manifestation of growth rates associated with each group. However, growth rates are the result of underlying urban processes that determine how a city's population changes over time, which we do not assess. Rather, this analysis took multiple static snapshots of the city size distribution as reflected in census data, and assessed each distribution for breaks, or gaps. Other processes that operate at specific scale-domains could also create discontinuous structure in city sizes irrespective of growth rate.

Nonetheless, prior research for the period 1836–1990 in France suggests there is a strong correlation between city size and growth rates, characterised by a nonlinear relationship between city population and growth rates (Guerin-Pace, 1995). Guerin-Pace (1995) asserted that this nonlinear relationship between city sizes and growth rates contributes to the spatial pattern of urban systems. Geographic location, topography and the transportation network associated with a particular city play an important role in determining city size in the real world (Mun, 1997). Regional systems developed within river basins, with social and economic ties along natural transportation corridors. Skinner and Henderson (1999) found that the line of attraction between two competing cities is not at an equal cost distance but is reflected in orientation to central places at the next higher level of the urban hierarchy and reinforced by the biophysical landscape. Geographic space is modified by the transportation network, which in turn leads to greater access to information, effectively reducing the distance between cities (Guerin-Pace, 1995). Improvements in transportation networks result in concentration of businesses and houses in a particular city, which in turn concentrates resources (Mun, 1997). Larger cities then manifest a greater 'sphere of influence', and can stunt the growth of smaller cities, which leads to increasing inequality between cities (Guerin-Pace, 1995). Overall, an alternative explanation of the stability we observe in this work could be due to natural advantages of certain locations. Davis and Weinstein (2002) found that the recovery of Japanese cities after WWII was inconsistent with Gibrat's law but consistent with the concept of natural advantages. Davis and Weinstein (2008) also found that cities not only recovered in proportion to initial damage after WWII but recovered the same pattern of industrial composition, again suggesting natural advantages for particular locations. Furthermore, Black and Henderson (2003) found that natural amenities such as coastal location, heating, cooling days and precipitation have a significant impact on the long-term growth of cities.

Regardless of the processes involved, which can only be speculative at this point, our results suggest that the structuring processes are persistent in time and space and create domains of opportunity and manifest as a robust hierarchical structure in urban systems. This has also been the case for species in an ecosystem, firm sizes and economies (Garmestani et al., 2006; Nash et al., 2014; Sundstrom et al., 2020).

From an empirical point of view, our findings allow us to observe an extremely stable discontinuous organisational urban structure, echoing research on regional urban systems in the United States (see Garmestani et al., 2009). This stability is remarkable considering that the two centuries studied cover events likely to modify the growth dynamics of cities. Whether it be the industrial revolution of the mid-19th century, the world wars of the 20th century or the intensification of peri-urbanisation in the 21st century, all these events were likely to profoundly modify the hierarchical structure of urban systems. However, this is not the case, as the urban structure is stable and discontinuous. What this analysis does not do is tell us about the movement of urban areas between size classes over the temporal span of this data set, which speaks to the robustness of urban systems to economic policy interventions. For example, if movement between size classes is rare, then this has implications for the success of economic policy interventions seeking to facilitate growth. Further research on this topic could explore the degree to which the urban structure is stable relative to the identity of the urban areas falling into each size class; self-organising processes within each size class could make urban systems largely resistant to interventions meant to promote growth.

Some unexplored research avenues arise from this observation. First, although this work demonstrates that a French regional urban system is discontinuous over space and time, it remains an open question as to whether French population data at the national level would have a similar pattern. Given the conflicting results in the Zipf or Pareto explorations at different geographic scales, it would be interesting to see whether the discontinuity hypothesis was robust across both national and sub-national levels of organisation. It remains unknown whether the processes that shape French regions are partially or fully unique between regions or between sub-national and national levels. The presence of discontinuities as well as the importance of the different scales of analysis (national and regional) to reveal specific structuring could be explored in further research testing for the presence of random growth and whether there is convergence towards a stationary state observable at all scales and subscales of urban systems. Second, the number of size classes in Nouvelle-Aquitaine appears to be shrinking over time. This trend has also been observed in global economies (Sundstrom et al., 2020) and may reflect increasing globalisation and a reduction in the number of different key processes that structure social systems, though more research is also needed in this area. Confirmation that this trend holds over other French regions would also be useful. Further research could enhance our understanding of city size distributions as they reflect scaling in complex adaptive systems and complement the existing literature in urban economics.

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Note

1. We draw attention to the reader that the data used by Lalanne and Zumpe (2020) and this paper are not strictly the same. We use census data from 1800 to 2015 for 106 urban areas from the Nouvelle-Aquitaine region, while Lalanne and Zumpe (2020) use the 250 most populated municipalities in France from 1793 to 2011. Thus, there are significant differences in both scale (regional versus national), and the population size range captured by each distribution.

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