sustainability

MDPI

Article

Patterns of Urban Spatial Expansion in European Cities

Gianni Guastella [1,2,*], Walid Oueslati [3] and Stefano Pareglio [1,2]

1 Centro di ricerca sull'Ambiente, l'energia e lo sviluppo sostenibile (CRASL), Università Cattolica del Sacro Cuore, 25121 Brescia, Italy; stefano.pareglio@unicatt.it
2 Fondazione Eni Enrico Mattei, 20123 Milan, Italy
3 Department of Economics, Management, Society, Agrocampus Ouest, 49045 Angers, France; walid.oueslati@agrocampus-ouest.fr
* Correspondence: gianni.guastella@feem.it

Received: 15 January 2019; Accepted: 28 March 2019; Published: 15 April 2019

check for updates

Abstract: In representing urban sprawl, the decline in population and employment density from the city centre to the periphery has been identified as the main character associated with the spatial expansion of built-up areas. Urban spatial discontinuity, which occurs when the urban fabric includes built-up or green areas and a relevant share of vacant spaces, has gained recent attention. In this paper, we use Global Human Settlement Layer data to track urbanisation dynamics in European Functional Urban Areas (FUAs) from 1990 to 2014. We represent urban sprawl as the spatial expansion of FUAs associated with either or both declining population density and increasing built-up area discontinuity. We also consider the association with the demographic trends that have been described as the primary driver of urban spatial expansion. We use configural frequency analysis to explore the local association between the different characters of sprawl. We found evidence that urban sprawl effectively took differentiated forms across European FUAs. Even though FUAs have generally become less dense and more disperse, our results show that the extent of these phenomena appears to be more contained in recent years than in previous decades. Both elements of sprawl characterise FUAs with a shrinking population, confirming the decoupling of urban development policies and demographic trends in cities. The results call for better controlled urban development, favouring compact cities and subjecting land-use changes to a perspective of urban population growth.

Keywords: urban sprawl; urban morphology; European cities; configural frequency analysis

---

1. Introduction

With almost 75% of the population living in urbanised areas, Europe is among the regions in the world where urbanisation has significantly impacted human well-being and is expected to have future impacts. Cities are places where production, knowledge, innovation and economic growth concentrate, and their strength is reinforced by agglomeration economies. Favouring frequent connections and proximity, cities are also places where the diffusion of knowledge and public goods provision best contribute to human well-being. Partly due to this enduring urban development, which resulted in an incessant land uptake and tremendous pressures on natural resources, environmental problems are concentrated in cities [1–3]. City expansion is responsible for increased transport-related emissions and the loss of open spaces and ecosystem services, especially biodiversity, and produces adverse effects on human health caused by lower walking and cycling and increased obesity, higher mortality and injury rates due to car accidents, and lower water and air quality.

The last decades marked a change in the demographic trends that produced critical consequences for the urbanisation process in Europe [4,5]. After World War II, we have witnessed a massive urbanisation during the period 1950–1960, with cities becoming progressively larger and denser, and later more dispersed, originating discontinuous urban fabrics [6,7]. The awareness about the potential consequences of an excessive soil sealing resulted in incomplete policy responses, and sprawl continues to represent one of the biggest challenges for the sustainability of cities [8]. Since the increase in the urban population will likely continue at a significant rate, according to population projections, understanding sprawl, its characters, determinants and consequences is of fundamental importance for planning and resource management policies. The objective of this paper is to elucidate the characters of urban sprawl in European cities.

The term *sprawl* has long been used in the debate about the changing functions and organisation of modern cities. It has been referred to by its opponents as the pure expansion of the extent of cities, assigning it a negative connotation justified by the loss of agricultural and natural land, the consequences on the environment and ecosystems and the increase in traffic, noise and congestion [9]. Economists contend that a spatial expansion of the urban area is necessary to accommodate both the increasing housing demand related to demographic and urbanisation trends, and the shift in preferences towards bigger and more isolated houses. Limiting the spatial expansion of cities would benefit the environment at the expense of private advantages of households. In addition to being fuelled by sentiment in favour of and against the spatial expansion of cities, the debate about urban sprawl has been dominated by the lack of a clear and unequivocal definition, and confusion between the phenomenon itself, its characteristic features, and its causes and consequences.

Sociologists, geographers, ecologists and economists provide diverging views and conceptualisations of sprawl, but a substantial body of the theoretical and empirical cross-disciplinary literature identifies the main characters of sprawling cities as low-density housing and the decentralisation of residential plots [10] following a distance–decay effect [11]. Several recent contributions noted the multiple dimensions that characterise sprawl, including discontinuity—and especially residential fragmentation. Galster et al. [12] define eight indicators related to urban sprawl: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses and proximity, and derive a synthetic indicator of urban sprawl for a sample of 13 US cities. Torrens [13] proposes a methodology to quantify urban sprawl with an application to the city of Austin in the US that is based on indicators of the total urbanised area, density, land-use mix and its spatial configuration, fragmentation and scattering and decentralisation. Schwarz [14] uses data-reduction techniques to explore synthetic measures of sprawl, including different indicators reflecting the spatial distribution of built-up area and population within cities. Based on the analysis of 231 cities in Europe, Schwarz [14] concludes that three synthetic indicators related to the built-up area, density, and discontinuity capture more than 50% of the total variance in the data. Arribas-Bel, Nijkamp, and Scholten [15] analyse European cities and apply self-organising maps to different indicators that, taken together, represent urban sprawl. In addition to density, they measure the fragmentation of space with a *scattering* index that is based on the number of urban patches, and four other indicators: the decentralisation of population, connectivity, availability of open spaces and land use mix. Jaeger and Schwick [16] and Hennig et al. [17] provide a definition of urban sprawl based on *weighted urban proliferation*, a concept and measurement tool that accounts for built-up area, density and dispersion. Building upon this evidence, in a sprawling city, the land-use per capita is generally high and is marginally increasing from the city centre to the periphery There is also alternation of built-up or green spaces and empty spaces—sometimes unplanned, often in the peripheral zones—or the realisation of detached city edges that create a substantial and variable discontinuity in the urban morphology.

These studies documented the relationship between the three main characteristics of urban sprawl: the total urbanised area, the distribution of the urban population over the urbanised area (density) and the distribution of the urbanised area over the city space (discontinuity). The study of the dynamics of these characters has received relatively little attention. Motivated by the absence of reliable and comparable historical series of data, many studies approached the analysis of urban sprawl with data reduction techniques or general multivariate analysis techniques based on cross-city data. Capturing correlations among variables via data reduction can show the global association between the variables, but an existing correlation at a single point in time cannot show how the measures co-evolve over time. In contrast, the analysis of their dynamics allows for disentangling local patterns of variations. This study explores the dynamics of these variables and proposes a methodological approach for this purpose.

The most difficult aspect of ongoing land transformation is the linkage with population growth, and more generally, with the related socio-economic changes. The spatial expansion of built-up areas is usually in response to the increase in demand for housing caused by a growing population [18], but increasing evidence documents how weak this relationship is in some circumstances. In modern cities, the demand for housing shifted from the centres to the peripheries, where the housing cost per square metre is lower because more land is available at a lower price, generating low- and very low-density suburban zones [19]. Furthermore, modern societies are moving towards lifestyles that consume more and more space per inhabitant [8] because people's living preferences for the contiguity to open spaces and for detached houses increasingly determine the fragmentation of the landscape [20]. As a result, there is evidence that urbanised areas also expanded in cities where the total population declined [21–24].

The objective of this paper is to understand the evolution of urban sprawl in Europe through a description of its main characters and link it to urban population dynamics. Sprawl is presented as multidimensional and measured by three metrics: the total built-up area, population density, and built-up area discontinuity. We study the changes in these variables in European cities, as defined by their functional urban areas (FUAs) and link them to changes in the urban population. The four dimensions provide a picture of the likely evolution of sprawl phenomena and can guide better informed and more sustainable planning. We consider cities where the urbanised area grew during the period considered (first factor) and study the patterns of variations in discontinuity and density (second and third factors, respectively) that occurred alongside the urban spatial expansion. The fourth factor is used to understand whether the configuration of sprawl changes in shrinking cities is the growth of the population. The period we consider is from 1990–2014, as there are only three time-points (1990; 2000; and 2014) for which the data are available. We construct two sub-periods of observation: 1990–2000; 2000–2014.

We use configural frequency analysis (CFA) [25–27] to search for clear patterns, i.e., combinations of the values of the three variables that reproduce a clear circumstance to relate to the growth of the urbanised area. CFA is a statistical technique for the multivariate analysis of data that is commonly employed in an exploratory fashion to find statistically uncommon patterns in the data. Although the paper is not aimed at deepening the methodological aspects, but rather at describing the relationship between the different characters of sprawl, the use of the CFA approach to detect specific patterns of urban sprawl is new in the literature and will be discussed. Differently from simple correlation analysis that captures global association between variables, CFA allows isolating local patterns of variations, hence subsamples of cities characterised by a specific association between the variables. Furthermore, the significance of these patterns can also be tested statistically.

Our reference data for the indicators in this paper is the Global Human Settlement Layer (GHSL) data. The GHSL dataset provides worldwide population density maps. Population data are provided in 250 m × 250 m grid cells, with the estimated number of inhabitants within each 62,500 m^2 (0.0625 km^2) cell surface reported for the same time points as the settlement data, i.e., for years 1975, 1990, 2000 and 2014. We use these data to measure urban sprawl in the 656 FUAs in Europe. The concept of the FUA in the EU interprets the general definition of a city used in the OECD (Organisation for Economic Co-operation and Development) classification [28] and includes an urban core and a periphery defined using a functional relations approach that is consistent across the EU Member States (MSs). Lacking a classification of cities based on the administrative borders that provides a list of comparable units across MSs, adoption of the FUA as a unit of observation in this paper appears to be the best approach to approximate cities in the EU.

The remainder of the paper is organised as follows. Section 2 reviews the literature, primarily comprising the debate about the conceptualisation and measurement of urban sprawl. Section 3 briefly describes the indicators and their main features and tracks the evolution of these indicators in the two sub-periods. We also describe how we employ CFA to explore the local patterns of associations among these indicators. The results are presented in Section 4. Section 5 discusses the results and concludes by drawing some policy implications.

2. Urban Sprawl Definition and Measurement

Over decades, the term "urban sprawl" has been widely, and perhaps incorrectly, used to represent the spatial expansion of cities. The spreading of cars as transport vehicles and the massive investment in road infrastructures, among others, have allowed for the increasing availability of people to commute over longer distances, accommodating the desire to live in larger houses, possibly with private gardens [29]. Advocates of the compact urban form contended that the private benefits related to such a model of urban planning came at a social cost. The loss of fertile soil for agriculture, progressive deforestation and degradation of various ecosystem services supplied by the agricultural and natural environments, including the loss of biodiversity, loss of the soil's capacity to act as a carbon sink, and alteration of the water cycles, add to what is perceived as the most detrimental consequence of urban sprawl: the increase in road congestion, air pollution and noise caused by commuting [1,3].

However, sprawl is more than the spatial expansion of cities. Urban spatial expansion responds to socio-demographic and environmental pressures. The urban population is growing fast, shifting the demand for houses. Current estimates predict that more than 80% of the European population will live in cities by 2050, requiring local administrations to face the new demand for houses. The changing economy and society also affect the demand for houses. Urbanisation economies driven by agglomeration factors and knowledge circulation in cities fostered the productivity growth that eventually translated into higher wages, especially in large metropolitan areas. The higher income increased the demand for larger houses, and sufficient space has often been found at a competitive price in the peripheries. Finally, the modernisation of existing transport infrastructures in conjunction with investments in support of its expansion facilitated people's mobility over longer distances and more frequent commuting, providing an incentive to live far from the city centre for households trading-off between a higher house price and a longer commute. As the spatial expansion of cities is the result of market dynamics, only the uptake of agricultural and natural land that is not justified by the socio-economic changes should be considered sprawl, according to economists [30]. The rationale behind the economists' argument is that, whenever land uptake benefits aggregate households' utility, it should not be regarded as a negative phenomenon [31]. It should be determined excessive land uptake when it follows the fact that the markets fail to internalise the negative externalities or there is low institutional attention of planners to the land use.

In addition to being fuelled by many diverse and usually contrasting conceptualisations, the debate about urban sprawl has been dominated by issues related to its measurement. Attempts to measure sprawl stem from the use of a single indicator such as the population density [32] with data reduction techniques aimed at deriving one synthetic indicator from a large set of information (See Jaeger et al. [10] for a review). The advantage of using one indicator is clear: it provides a simple, measurable, comparable and straightforward way to interpret a picture of the state of the art and evolution of the phenomenon over time. The drawbacks are as clear: it does not account for the multiple dimensions of the phenomenon, and the same level of population density may reflect very different spatial distributions of population and urbanised areas across the space of a city. Data reduction exercises also have significant weaknesses, especially in interpreting the value of the aggregated indicator and selecting the variables expected to present the multiple dimensions of urban sprawl. Interpretation of the resulting indicator is far less straightforward than the interpretation of basic indicators. Furthermore, in attempting to represent the economic and social dimensions associated with urban sprawl in a synthetic measure, studies frequently select variables that measure the causes (e.g., the structure of road and rail networks, the use of cars as a preferred transportation method) and consequences (e.g., urban segregation, supply of urban services) of urban sprawl rather than the phenomenon itself. As a result, the use of composite sprawl indicators has limited potential to inform decision makers.

Understanding the spatial distribution of the population and urbanised area and mapping the state and evolution of population density are extremely relevant to inform planners and decision makers. Many of the negative consequences commonly associated with urban sprawl are linked to how the people and built-up area are distributed in space rather than with the average number of inhabitants in the built-up area. For instance, a low-density urban structure makes the provision of public transportation uneconomical, incentivising the use of private cars while increasing the average distance commuted. In addition, a high discontinuity of urban settlements increases the distance between consumers and the providers of basic public and private services, such as schools, leisure facilities, and supermarkets, requiring people to commute for work and for everyday necessities. Moreover, while low density increases the average trip length, discontinuity impacts the number of trips and the combination of both has the most detrimental effects on emissions, pollution and noise. The same happens with the ecosystems. In general, low-density levels are associated with higher land consumption per capita and lower fractions of land that can effectively supply ecosystem services, and fragmentation of the non-urban space limits the potential of the ecosystems to provide these services effectively.

Considering the critiques of the use of a single indicator and aggregated indicators, some measures of sprawl weigh the need to take the multi-dimensional nature of sprawl into account to provide a clear and unequivocal picture of the problem. An example of this can be found in the recent EEA-FOEN (European Environment Agency and Swiss Federal Office for the Environment) report on urban sprawl in Europe (EEA-FOEN, 2016) [8] and the OECD report on urban sprawl in OECD countries [33]. Both reports are good examples of how to determine the spatial distribution of the population and built-up area in combination with analyses based on population density. The EEA-FOEN report introduced the weighted urban proliferation (WUP) indicator, the weighted product of different but straightforward dimensions including dispersion, a measure that quantifies the spatial distribution of the built-up area and land-use per inhabitant (LUP), the reciprocal of the population density. The OECD report operationalises the multi-dimensional conceptualisation of urban sprawl into a set of different indicators expressing urban land cover and land-use mix, built-up area discontinuity, the centrality of the core, population density and its spatial distribution.

Although a precise definition of urban sprawl is far from being universally agreed upon, its multi-dimensional nature is now commonly accepted, meaning that the relationships between the different dimensions are well understood. The patterns of evolution of the multiple dimensions of urban sprawl have been less studied. The development of empirical literature investigating the dynamics of urban sprawl has been hampered by the lack of consistent data about the urban population, urbanised area, density and its spatial distribution over sufficiently long time-spans.

3. Materials and Methods

The unit of analysis in this paper is the FUA. The FUA is a newly introduced spatial unit that includes the city centre and its commuting zone (formerly known as the larger urban zone (LUZ). The EU (Eurostat), in collaboration with the OECD, developed a harmonised definition of urban areas as "functional economic units", overcoming previous limitations linked to administrative units. As building blocks for functional urban areas, this definition uses the smallest administrative units for which national commuting data are available [28]. The core centres are identified based on gridded population data and consist of continuous clusters of cells with population density larger than 1500 inhabitants. The hinterlands are defined based on commuting data: a municipality is part of the FUA if at least 15% of the resident population works in the urban core. The FUA dataset includes EU25 member states plus Switzerland and Norway, but is not yet updated to consider those member states that very recently joined the EU like Romania, Bulgaria and Croatia. The full list of FUAs is available in Table S1 as on-line Supplementary Material.

Data on the total built-up area, population, population density and discontinuity of the built-up space are sourced from the Global Human Settlement Layer (GHSL), an open tool of the European Commission Joint Research Centre that tracks human presence on the planet over time [34]. The GHSL data are provided at a high-resolution spatial scale and combines population data from census information and built-up area data from satellite images at four observation points in time, 1975, 1990, 2000 and 2014. We excluded the year 1975 from our analysis because all the cities from 1975–1990 show very similar dynamics characterised by a growing population and urbanised area, declining density and increasing discontinuity, and it was not possible to detect local patterns of variation in the sample.

The empirical approach of this paper follows the theoretical conceptualisation of urban sprawl as a multi-dimensional phenomenon with the three most relevant characters, the urban spatial expansion, the settlement discontinuity, and the density of population, associated with demographic changes. Demographic changes are relevant because most FUAs are experiencing a shrinking population and their urbanised area is growing nonetheless [22], leading to lower land-use per inhabitant and greater discontinuity, and hence more sprawl. Table 1 provides a list of variables employed and a short description of how each variable is computed for each FUA.

Table 1. Description of the variables.

Variable	Description
BUA—Built-up area	Total built-up area in square metres, calculated as the product of (a) the number of cells with built-up area greater than 0; (b) mean built-up area per built-up cell
POP—Population	Total number of inhabitants in the FUA
DENS—Population density	Average number of inhabitants per square metre of built-up area
DISC—Discontinuity	Number of fragments of artificial area over the total area of cells where more than 50% of the area is built-up

To describe the general trend in EU cities from 1990–2014, Figure 1 shows the dynamics of the two most significant characters of sprawl, population density and built-up area discontinuity, on the horizontal and vertical axes, respectively, to map the situation of each city. There is no clear correlation between the two characters of sprawl. Both distributions show extreme values that appear independently. The largest increase in population generally occurred in FUAs where the population density increased independently of the level of built-up area discontinuity. Although this is clearly the result of densification occurring in many European FUAs, evidence also suggests that the population density is declining, and built-up area discontinuity is increasing in FUAs where the population is shrinking. It may appear obvious unless one also considers that the total built-up area has grown in these cities, resulting in the worst possible form of urban sprawl. In addition to preliminary considerations about urban sprawl, the figure reveals that, even in the absence of global correlations between the variables, detection of local clusters can best inform about the co-evolution of the variables that primarily contribute to urban sprawl.

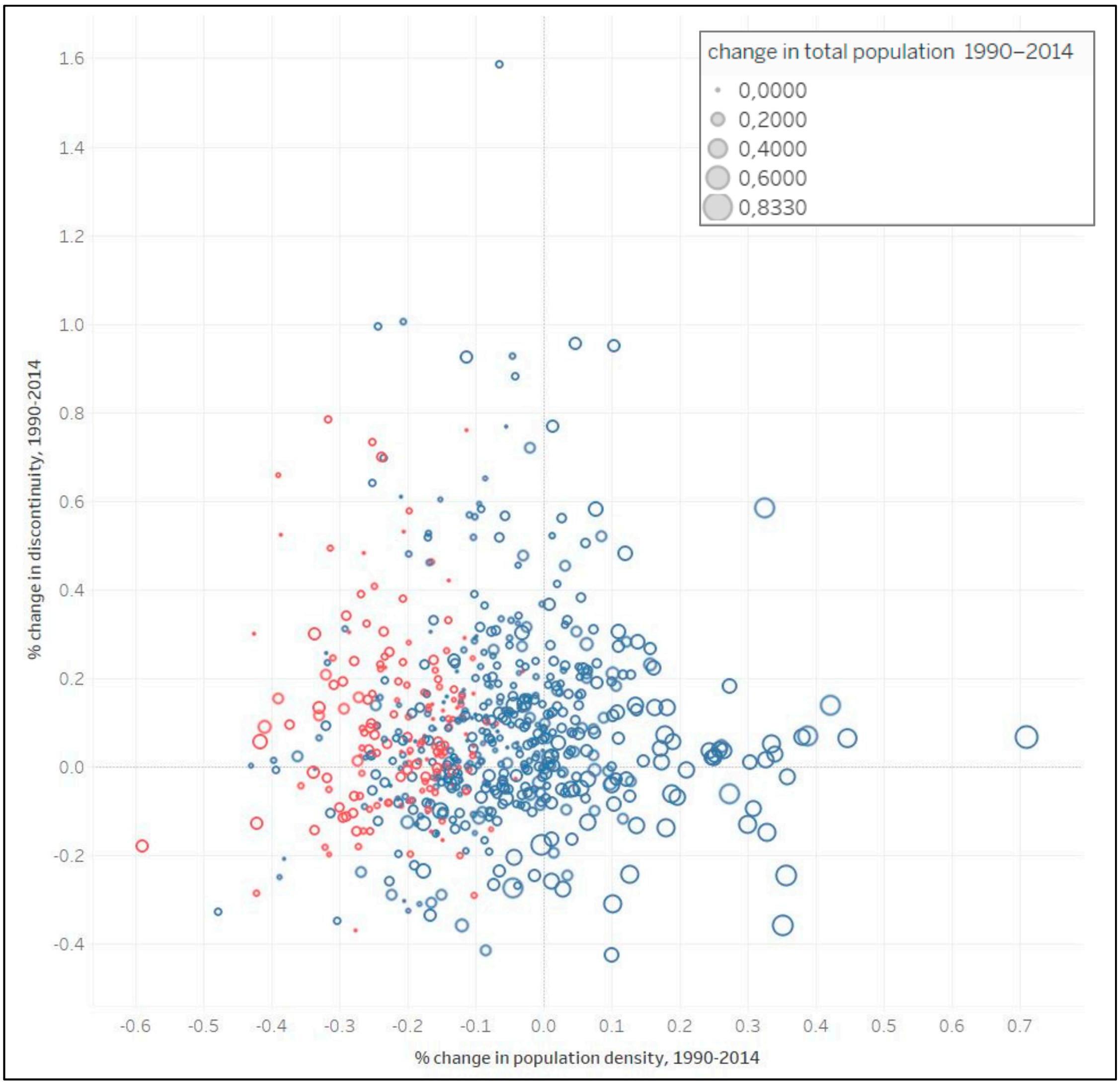

Figure 1. Dynamics of population density and built-up area discontinuity in European cities, 1990–2014. The figure compares the change in population density (horizontal axis) and discontinuity (vertical axis) in the sample of European functional urban areas (FUAs). The size of the circle shows the absolute value of the percentage change in total population in the relative FUA; a red circle indicates that the population is shrinking, a blue one a population that is growing. The values of population change in decimal points corresponding to the size of the circle are reported in the upper-right part of the figure. Three cities (Tallinn, Guadalajara and Walbrzych) have been excluded because a population growth greater than 100% makes them outliers in this figure. Source: own elaboration based on Global Human Settlement Layer (GHSL) data.

To study the dynamics of the variables and analyse local patterns of variations, we made some simplifying assumptions. First, we assumed that the dynamics of the variables of interest can be described with discrete variables taking the values −1, 0, 1 if the value of the variable decreases, remains stable, or increases in the city, respectively. This process clearly hinders large variation, especially in the extremes, but it considerably simplifies the description of the dynamics without changing the overall picture. Second, we assumed that small variations in either direction should not be considered. This assumption guarantees that a sufficient number of observations was assigned a value equal to 0 for each variable and that sufficiently small movements in the value of the variable were not considered equivalent to relatively larger movements. In the analysis, we considered small a variation that was below 1%.

The starting point of the empirical analysis was the built-up area. We selected the sample considering only the FUAs that grew in the reference period, meaning that the total built-up area (BUA) increased by at least 1%. This translates into a sample size of 644 for 1990–2000 and 652 for 2000–2014. Letting $X = [POP, DENS, DISC]$ denote the vector of percentage changes in the total urban population, population density, and urban discontinuity, respectively, in the sample FUAs, we define the vector of categorical variables $x = [Pop, Dens, Disc]$ taking values of 1, 0, −1 if the related change was positive, zero or negative, respectively, as follows:

$$x_i^j = \begin{cases} 1 & if \quad X_i^j > 0.01 \\ 0 & if \quad -0.01 \leq X_i^j \leq 0.01 \\ -1 & if \quad X_i^j < -0.01 \end{cases} \qquad i = 1, 2, N; j = Pop, Dens, Disc \tag{1}$$

Table 2 presents the empirical (relative) frequencies of the distributions of the indicators for each sub-period. From 1990–2014, the population increased in 72% of the FUAs in the sample. The most frequent character of the urban spatial expansion was the low-density development of land, as we observed a decline in density in 72.6% of the FUAs in the sample. During the same period, the discontinuity followed irregular patterns, increasing in more than half of the FUAs in the sample and decreasing in 29% of the FUAs. Overall, the statistics provided a very clear picture of the dynamics of urban spatial expansion in EU FUAs during this period. Almost all the FUAs experienced increases in the built-up area, accompanied by an increase in population in many cases that, in the best case, was insufficient to compensate for the increase in built-up area to maintain a constant ratio. The development of natural or agricultural land substantially impacted the urban morphology, increasing the number of plots of artificial area in more than a half of the FUAs.

Table 2. Distribution of the indicators from 1990–2014 and in two sub-periods.

	1990–2014 (N = 656)			**1990–2000 (N = 644)**			**2000–2014 (N = 652)**		
	Pop	**Dens**	**Disc**	**Pop**	**Dens**	**Disc**	**Pop**	**Dens**	**Disc**
Decrease: −1	0.222	0.726	0.287	0.194	0.756	0.185	0.230	0.673	0.320
Stability: 0	0.056	0.043	0.144	0.129	0.095	0.258	0.090	0.064	0.216
Growth: 1	0.722	0.231	0.569	0.677	0.149	0.557	0.679	0.262	0.463

Comparing the two sub-periods of 1990–2000 and 2000–2014, there was evidence of continuous population growth in the majority of FUAs, even though more FUAs experienced population shrinking in the second sub-period than in the first. In addition, the first sub-period was characterised by a larger share of FUAs experiencing a declining population density and an increasing residential discontinuity. Overall, the incidence of sprawl, resulting from the combination of declining density and increasing discontinuity, appears to be larger in the first sub-period.

The objective of the CFA investigation was to determine the extent that the two phenomena (declining density and increasing discontinuity) appeared simultaneously in the FUAs in relation to the population dynamics. It does so by comparing two pieces of information: the number of sample units in which a specific pattern of urban sprawl is observed and the number of units in which we should expect to observe it under the hypothesis that the characters of urban sprawl are independent. Applications of CFA are common in psychological studies [27]. Exploratory CFA is employed to map the possible combinations of categorical variables and describe their frequencies. In the case of urban sprawl, it can be used to map all the possible combinations of changes in density, discontinuity and population that are associated to a spatial expansion of the artificial area. Inferential CFA is employed to analyse local associations between variables by identifying atypical occurrences in the combination of variables. Identification of the atypical occurrences is based on statistical tests to determine the frequency of the joint distribution associated with that pattern and the expected frequency under the null hypothesis (usually of independence). In the case of urban sprawl, inferential CFA is used to capture the association between the multiple characters of sprawl in the different sub-samples of cities.

Using the marginal distribution information in Table 2, for each possible combination of the values of Pop, Dens and Disc, we computed the expected number of observations $E\ (n)$ under the hypothesis that the three variables were independent using the formula in Equation (2), where m is any value in the set $m = \{G;S;D\}$ (Growth, Stability, Decrease) and $p_G^j = p\left(x^j = 1\right)\ p_S^j = p\left(x^j = 0\right) p_D^j = p\left(x^j = -1\right)$ and N is the total sample size [25].

$$E\left(n \middle| m_{pop}, m_{dens}, m_{disc}\right) = N \cdot p_m^{pop} \cdot p_m^{dens} \cdot p_m^{disc} \tag{2}$$

Thus, considering the case of FUAs in which we observe a decrease in all variables, using the estimates in Table 2, for 2000–2014, $p(pop = Decrease) = 0.230$, $p(dens = Decrease) = 0.673$, and $p(disc = Decrease) = 0.320$, the expected number of observations under the null hypothesis that the variables are not correlated was approximately 32.3, with N equal to 652 in this period.

An atypical combination arises whenever the observed frequency is significantly different from the expected one. A "type" defines a special combination in which the observed frequency (f^o) is larger than the expected (f^e), and the opposite holds for the "antitype". We used the statistics in Equations (3) and (4). to test the null hypothesis that the difference was not statistically significant, and using a conservative approach, we determined that the difference was statistically significant when both the tests rejected the null hypothesis at least at a 5% significance level.

$$\frac{(f^o - f^e)^2}{f^e} \sim \chi^2 \tag{3}$$

$$\frac{f^o - f^e}{\sqrt{f^e\left(1 - \frac{f^e}{m}\right)}} \sim z \tag{4}$$

4. Results

We present the empirical analysis results, excluding patterns that resulted in an observed frequency equal to zero because the pattern was not represented in the sample of FUAs. Table 3 provides an overview of the results for 1990–2014 and the two sub-periods of 1990–2000 and 2000–2014. The first column is a numerical sequence that identifies a single pattern and the second, third and fourth columns represent the characters of the pattern through the values of the categorical variables. The values of −1, 0, 1 indicate whether the variable, i.e., the total population (Pop), population density (Dens), urbanisation discontinuity (Disc), decreased, remained stable, or increased. For the whole period and the two sub-periods, the first pair of columns enumerates the observed and the expected frequencies expressing the empirical distribution of the observations across the patterns and the theoretical (joint) distribution computed based on the marginal distributions of the variables. Types and antitypes are marked with (+) and (−), respectively. The last two columns per period report the computed values of the χ^2 and z statistics in Equations (3) and (4), with the respective p-values in brackets. The p-value of the z-test refers to the one-tail hypothesis that the difference between the observed and expected frequency was different from zero (either larger or smaller, depending on the sign). The rows are ordered by descending number of observed frequencies in the overall period.

Table 3. Configural frequencies of urban sprawl indicators in EU FUAs, 1990–2014.

#	pattern			1990–2014					1990–2000					2000–2014				
	Pop	**Dens**	**Disc**	**obs.**	**exp.**	**T**	**χ^2 (*p*)**	**z (*p*)**	**obs.**	**exp.**	**T**	**χ^2 (*p*)**	**z (*p*)**	**obs.**	**exp.**	**T**	**χ^2 (*p*)**	**z (*p*)**
21	1	−1	1	155	194.995	−	−2.864 (0.002)	−3.419 (0.000)	147	183.80	−	−2.714 (0.003)	−3.211 (0.001)	100	138.159	−	−3.246 (0.001)	−3.657 (0.000)
19	1	−1	−1	98	98.546		−0.055 (0.478)	−0.06 (0.476)	67	60.92	+	0.778 (0.218)	0.818 (0.207)	88	95.614	−	−0.779 (0.218)	−0.843 (0.200)
27	1	1	1	94	61.988	+	4.066 (0.000)	4.274 (0.000)	57	36.23	+	3.450 (0.000)	3.552 (0.000)	81	53.816	+	3.706 (0.000)	3.869 (0.000)
3	−1	−1	1	83	59.903	+	2.984 (0.001)	3.131 (0.001)	70	5.27	+	2 384 (0.009)	2 488 (0.006)	74	46.781	+	3.98 (0.000)	4.131 (0.000)
25	1	1	−1	41	31.327	+	1.728 (0.042)	1.771 (0.038)	9	12.01	−	−0.868 (0.193)	−0.877 (0.190)	55	37.244	+	2.91 (0.002)	2.996 (0.001)
20	1	−1	0	40	49.273		−1.321 (0.093)	−1.374 (0.085)	65	84.99	−	−2.168 (0.015)	−2.327 (0.010)	43	64.505	−	−2.678 (0.004)	−2.821 (0.002)
1	−1	−1	−1	37	30.274		1.223 (0.111)	1.252 (0.105)	24	17.47	+	1.563 (0.059)	1.585 (0.057)	38	32.375	+	0.989 (0.161)	1.014 (0.155)
2	−1	−1	0	25	15.137	+	2.535 (0.006)	2.565 (0.005)	31	24.37	+	1.344 (0.089)	1.370 (0.085)	38	21.841	+	3.458 (0.000)	3.517 (0.000)
12	0	−1	1	25	15.286	+	2.485 (0.006)	2.514 (0.006)	51	34.99	+	2.707 (0.003)	2.783 (0.003)	23	18.4	+	1.072 (0.142)	1.088 (0.138)
26	1	1	0	16	15.664		0.085 (0.466)	0.086 (0.466)	30	16.75	+	3.236 (0.001)	3.279 (0.001)	35	25.126	+	1.97 (0.024)	2.009 (0.022)
24	1	0	1	15	11.494		1.034 (0.151)	1.043 (0.148)	34	23.02	+	2.288 (0.011)	2.330 (0.010)	23	13.218	+	2.691 (0.004)	2.718 (0.003)
23	1	0	0	8	2.905	+	2.99 (0.001)	2.997 (0.001)	20	10.65	+	2.867 (0.002)	2.891 (0.002)	9	6.171	+	1.139 (0.127)	1.144 (0.126)
10	0	−1	−1	7	7.725		−0.261 (0.397)	−0.262 (0.397)	12	11.60	+	0.118 (0.453)	0.119 (0.453)	19	12.734	+	1.756 (0.040)	1.773 (0.038)
11	0	−1	0	5	3.862		0.579 (0.281)	0.581 (0.281)	20	16.18	+	0.950 (0.171)	0.962 (0.168)	16	8.591	+	2.528 (0.006)	2.545 (0.005)
22	1	0	−1	5	5.809		−0.336 (0.369)	−0.337 (0.368)	7	7.63	−	−0.228 (0.410)	−0.230 (0.409)	9	9.148	−	−0.049 (0.481)	−0.049 (0.480)
15	0	0	1											1	1.76	−	−0.573 (0.283)	−0.574 (0.283)

From 1990–2014 and in the two sub-periods, the most common pattern was #21. With values of Pop = 1, Dens = −1, and Disc = 1, the pattern was associated with an increase in the overall population with a decrease in the average density and an increase in the discontinuity. There were 155 FUAs in this group for the overall period and 147 and 100 from 1990–2000 and 2000–2014, respectively, decreasing in the second sub-period. The most harmful consequences for the environment were associated with this urban development pattern, the number of FUAs in this group was lower than expected. Patterns #3 and #12 describe the same urban development pattern characterised by decreasing density and increasing discontinuity occurring in FUAs where the total population is either decreasing (#3) or at least not increasing (#12). In both cases, the observed frequency was statistically larger than expected (except pattern #12 from 2000–2014), indicating that the coupling of a decreasing density and increasing discontinuity was associated with a stable or decreasing population. These FUA represent 108 observations in our sample (16.5% of the total) during the overall period and 121 and 97 observations in the two sub-periods, respectively. The low-density and high-discontinuity urban development pattern characterises 263 FUAs in the overall sample (40% of the total), 268 from 1990–2000 and 197 from 2000–2014.

A second very common type of urban development is described by the decrease in population density that occurs with either an increase in or stability of the residential discontinuity. Patterns #19 and #20 represent this typology of urban development in FUAs where the total population increased. From 1990–2014 as many as 98 FUAs composed the group characterised by a decrease of both density and discontinuity and 40 FUAs were characterised by a decrease in the density but not in the discontinuity. Both patterns are not classified as either types of antitypes, as the difference between the observed and expected frequencies was not significantly different from zero. For pattern #20, the difference was statistically lower than zero in both sub-periods, indicating a negative association between the probability of observing a decline in density and the probability of observing a stable residential discontinuity. Surprisingly, the correlation turned positive in FUAs where the total population decreased during the sub-periods (pattern #2), as the difference between the associated observed and expected frequencies was larger than zero and statistically significant for the whole period and the two sub-periods (although at a 10% significance level only in the first sub-period).

Summarising the results regarding the development patterns that showed the most detrimental consequences for the environment, which were patterns characterised by decreasing density and non-decreasing discontinuity, the main conclusion was that, in FUAs where the total population increased, there was evidence of a negative association between a decrease in density and an increase in discontinuity. In contrast, the association between the two became positive in FUAs where the population decreased over time. This evidence corroborates the argument of a continuous decoupling of urban planning and demographic trends.

The results also indicate patterns of virtuous urban development and patterns of increasing population density. The first of these patterns was #27: in these FUAs, the population increased relatively more than the urbanised area, causing an increasing average density, and the discontinuity increase prevented these FUAs from transforming into more compact cities. Fifty-five FUAs, less than 10% of the sample FUAs, were represented in pattern #25 and showed an environmental virtuous urban development pattern characterised by both increasing density and decreasing discontinuity from 2000–2014. In this case, the association between the three characters was positive, as the number of observed frequencies was statistically higher than the number of expected ones. Notably, this statistical association was not confirmed by the results for 1990–2000.

The results for 1990–2014 are summarised in Figure 2, which maps the European FUAs in the sample according to the pattern of urban development. Triangles strongly dominate countries such as France, Italy, Germany, Belgium and the Netherlands, as their cities were mostly characterised by an increased population and a decreased density with a discontinuity level that decreased (green triangles) or remained stable (blue triangles) over time. Red squares denote the worst possible urban sprawl when the declining density occurred with increasing discontinuity. These cities were concentrated in

Eastern European countries, although there were small clusters in Germany and north-eastern France and in Spain and southern Italy. A particular case of urban transformation that requires attention is the case of shrinking cities depicted as orange squares. In this case, there is a high spatial concentration of occurrences in specific areas of Europe, such as north-western Spain, southern Italy, and northern Germany. Stars indicate urban patterns characterised by an increasing density and an increasing (green stars) or stable (yellow stars) discontinuity and both patterns show an evident spatial concentration. In the first case, the cities were predominantly located on the east coast of Spain, the south coast of France, and the alpine region at the border between Italy and Switzerland. The second case was that of many cities in the UK and almost all cities in Finland, Sweden and Norway.

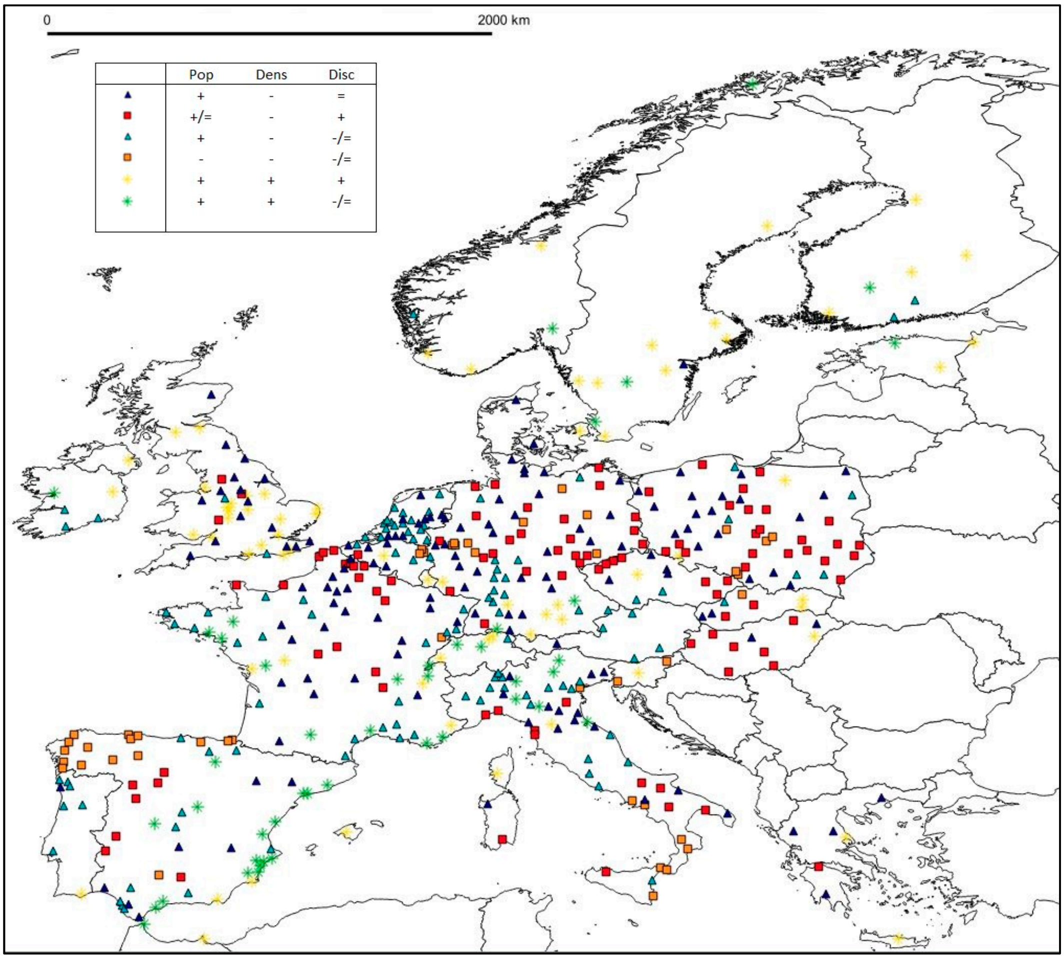

Figure 2. Spatial distribution of the patterns of urban development. EU cities on the map are classified according to the changes in population, density, and discontinuity from 1990–2014. Patterns are explained in the legend. Source: own elaboration based on GHSL data.

5. Discussion

This study approached urban sprawl with the perspective of the dynamic co-evolution of various factors that recent growing literature identifies as the multiple dimensions of urban sprawl. These multiple dimensions concern the spatial distribution of the population, the urbanised area, and the average built-up area per inhabitant, the inverse of which is considered a standard indicator of urban sprawl. In this study, based on observation of the population and built-up area for European cities in 1990, 2000 and 2014, we consider the dynamics of the total built-up area, total population, population density, and the dispersion of the built-up area across the city's boundaries.

Investigating the dynamics of urban sprawl can help understand the effectiveness of policy instruments to contrast urban sprawl. The fact that several dimensions of urban sprawl coexist in the same phenomenon means that urban sprawl can manifest in different manners depending on how the dimensions occur in a specific city. This means that the phenomenon requires differentiated and context-specific solutions to be achieved through adequate instruments. Moreover, the co-existence of multiple dimensions of urban sprawl does not imply that these dimensions will co-evolve over time. In contrast, these dimensions will follow differentiated trajectories that lead to complex patterns of urban sprawl, and thus recognising the specific pattern is a first step in designing policy actions tailored to the particular context and mode in which the urban sprawl is occurring.

Our analysis of European cities reveals a strong linkage between changes in density and changes in built-up area discontinuity. However, the association was positive only in cities where the total population had not increased over time despite the growth of the total built-up area. This evidence suggests that urbanisation in general and urban sprawl specifically are increasingly decoupled from demographic dynamics and are likely the result of the relocation of households from city centres to peripheries. In the absence of population growth, the construction of new housing units in low-density and highly discontinuous neighbourhoods generates social costs and negative externalities that cannot be compensated by the private benefits, which are very limited and restricted to small portions of the population. In contrast, the association between changes in the population density and built-up area discontinuity was negative in cities where the population was expanding; although the average density was decreasing, these cities have become more compact from a morphological perspective. Thus, regulatory frameworks constraining the amount of land conversion and the location of plots to be converted to current and prospective demographic dynamics can be effective to counteract both the overall growth of built-up area that cannot be justified by the increasing housing demand and the sprawling of cities.

Another important result of this paper is that changes in population density and built-up area discontinuity do not always occur in tandem. This is true in sprawling cities, where a decline in density may be accompanied by an increase in discontinuity, and in cities that maintain an environmentally virtuous urban development pattern, i.e., cities where the population density is increasing. This evidence calls for place-specific and context-specific solutions for the problem of urban sprawl that are tailored to the characters of urban sprawl. Policy instruments designed to promote socially desirable levels of density may fail to adequately assess the issue of built-up area discontinuity, as in the case of urban containment policies that may eventually generate leapfrog urban development. Whenever decreasing density and increasing fragmentation occur in tandem, specifically designed policies that possibly mix several regulatory instruments may succeed where policies intended to solely promote high-density urban development may fail.

The third result of this paper is that the combinations of changes in total population, population density and built-up area discontinuity are not randomly distributed in space and are strongly concentrated in specific geographical regions of Europe. The spatial concentration of these factors is known to be particularly harmful for the environment and the health of citizens for their effects on warming [35–38] and the quality of air as well [9,39–41]. This evidence links the occurrence of sprawl to the general socio-economic, geographic and institutional settings at an intermediate level between the state and the city. At a glance, this appears to be the regional or macro-regional level in Europe.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/8/2247/s1, Table S1: List of Functional Urban Areas in the Sample.

Author Contributions: G.G. is the lead author of this paper. He drafted most of the text and was the main actor in collecting and mining the data. W.O. helped to focus the research question and the used methodology before joining the OECD as Senior Economist. However, worth mentioning that the opinions expressed in this paper are those of the authors and do not necessarily reflect the official views of the OECD or of the governments of its member countries. S.P. contributed to define the research question and to derive the policy implications in the discussion of the results.

Funding: This research received no external funding.

Acknowledgments: We thank the three anonymous referees for providing useful suggestions and comments. The usual disclaimers apply.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ewing, R.H. Characteristics, Causes, and Effects of Sprawl: A Literature Review. In *Urban Ecology: An International Perspective on the Interaction between Humans and Nature*; Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., Simon, U., ZumBrunnen, C., Eds.; Springer: Boston, MA, USA, 2008; pp. 519–535. ISBN 978-0-387-73412-5.
2. Hartig, T.; Kahn, P.H. Living in cities, naturally. *Science* **2016**, *352*, 938–940. [CrossRef] [PubMed]
3. Johnson, M.P. Environmental Impacts of Urban Sprawl: A Survey of the Literature and Proposed Research Agenda. *Environ. Plan. A* **2001**, *33*, 717–735. [CrossRef]
4. Gerland, P.; Raftery, A.E.; Ševčíková, H.; Li, N.; Gu, D.; Spoorenberg, T.; Alkema, L.; Fosdick, B.K.; Chunn, J.; Lalic, N.; et al. World population stabilization unlikely this century. *Science* **2014**, *346*, 234–237. [CrossRef]
5. Montgomery, M.R. The Urban Transformation of the Developing World. *Science* **2008**, *319*, 761–764. [CrossRef] [PubMed]
6. Oueslati, W.; Alvanides, S.; Garrod, G. Determinants of urban sprawl in European cities. *Urban Stud.* **2015**, *52*, 1594–1614. [CrossRef] [PubMed]
7. Kasanko, M.; Barredo, J.I.; Lavalle, C.; McCormick, N.; Demicheli, L.; Sagris, V.; Brezger, A. Are European cities becoming dispersed: A comparative analysis of 15 European urban areas. *Landsc. Urban Plan.* **2006**, *77*, 111–130. [CrossRef]
8. EEA-FOEN. *Urban Sprawl in Europe: Joint EEA-FOEN Report*; European Environmental Agency—Swiss Federal office for the Environment: Luxembourg, 2016; ISBN 978-92-9213-738-0.
9. Wilson, B.; Chakraborty, A. The Environmental Impacts of Sprawl: Emergent Themes from the Past Decade of Planning Research. *Sustainability* **2013**, *5*, 3302–3327. [CrossRef]
10. Jaeger, J.A.G.; Bertiller, R.; Schwick, C.; Kienast, F. Suitability criteria for measures of urban sprawl. *Ecol. Indic.* **2010**, *10*, 397–406. [CrossRef]
11. Guastella, G.; Pareglio, S. Spatial analysis of urbanization patterns: The case of land use and population density in the Milan Metropolitan Area. *Rev. Urban Reg. Dev. Stud.* **2017**, *29*, 89–102. [CrossRef]
12. Galster, G.; Hanson, R.; Ratcliffe, M.R.; Wolman, H.; Coleman, S.; Freihage, J. Wrestling Sprawl to the Ground: Defining and measuring an elusive concept. *Hous. Policy Debate* **2001**, *12*, 681–717. [CrossRef]
13. Torrens, P.M. A Toolkit for Measuring Sprawl. *Appl. Spat. Anal.* **2008**, *1*, 5–36. [CrossRef]
14. Schwarz, N. Urban form revisited—Selecting indicators for characterising European cities. *Landsc. Urban Plan.* **2010**, *96*, 29–47. [CrossRef]
15. Arribas-Bel, D.; Nijkamp, P.; Scholten, H. Multidimensional urban sprawl in Europe: A self-organizing map approach. *Comput. Environ. Urban Syst.* **2011**, *35*, 263–275. [CrossRef]
16. Jaeger, J.A.G.; Schwick, C. Improving the measurement of urban sprawl: Weighted Urban Proliferation (WUP) and its application to Switzerland. *Ecol. Indic.* **2014**, *38*, 294–308. [CrossRef]
17. Hennig, E.I.; Schwick, C.; Soukup, T.; Orlitová, E.; Kienast, F.; Jaeger, J.A.G. Multi-scale analysis of urban sprawl in Europe: Towards a European de-sprawling strategy. *Land Use Policy* **2015**, *49*, 483–498. [CrossRef]
18. Paulsen, K. Yet even more evidence on the spatial size of cities: Urban spatial expansion in the US, 1980–2000. *Reg. Sci. Urban Econ.* **2012**, *42*, 561–568. [CrossRef]
19. Guastella, G.; Pareglio, S.; Sckokai, P. A spatial econometric analysis of land use efficiency in large and small municipalities. *Land Use Policy* **2017**, *63*, 288–297. [CrossRef]
20. Turner, M.A. Landscape preferences and patterns of residential development. *J. Urban Econ.* **2005**, *57*, 19–54. [CrossRef]
21. Couch, C.; Karecha, J.; Henning Nuissl, P.; Rink, D. Decline and sprawl: An evolving type of urban development—observed in Liverpool and Leipzig. *Eur. Plan. Stud.* **2005**, *13*, 117–136. [CrossRef]
22. Haase, D.; Kabisch, N.; Haase, A. Endless Urban Growth? On the Mismatch of Population, Household and Urban Land Area Growth and Its Effects on the Urban Debate. *PLoS ONE* **2013**, *8*, e66531. [CrossRef]
23. Hoymann, J. Accelerating urban sprawl in depopulating regions: A scenario analysis for the Elbe River Basin. *Reg. Environ. Chang.* **2011**, *11*, 73–86. [CrossRef]
24. Rienow, A.; Stenger, D.; Menz, G. Sprawling cities and shrinking regions—Forecasting urban growth in the ruhr for 2025 by coupling cells and agents. *Erdkunde* **2014**, *68*, 85–107. [CrossRef]

25. Von Eye, A. Configural Frequency Analysis. Wiley StatsRef: Statistics Reference Online. 2014. Available online: https://onlinelibrary.wiley.com/doi/full/10.1002/9781118445112.stat06143 (accessed on 8 April 2019).
26. Von Eye, A. *Introduction to Configural Frequency Analysis: The Search for Types and Antitypes in Cross-Classifications*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 1990; ISBN 978-0-521-38090-4.
27. Von Eye, A.; Peña, E.G. Configural Frequency Analysis: The Search for Extreme Cells. *J. Appl. Stat.* **2004**, *31*, 981–997. [CrossRef]
28. OECD. *Redefining 'Urban': A New Way to Measure Metropolitan Areas*; OECD Publishing: Paris, France, 2012.
29. Glaeser, E.L.; Kahn, M.E. Sprawl and urban growth. In *Handbook of Regional and Urban Economics*; Elsevier: Amsterdam, The Netherlands, 2004; Volume 4, pp. 2481–2527.
30. Brueckner, J.K.; Fansler, D.A. The Economics of Urban Sprawl: Theory and Evidence on the Spatial Sizes of Cities. *Rev. Econ. Stat.* **1983**, *65*, 479. [CrossRef]
31. Brueckner, J.K. Urban sprawl: Diagnosis and remedies. *Int. Reg. Sci. Rev.* **2000**, *23*, 160–171. [CrossRef]
32. Hasse, J.E.; Lathrop, R.G. Land resource impact indicators of urban sprawl. *Appl. Geogr.* **2003**, *23*, 159–175. [CrossRef]
33. OECD. *Rethinking Urban Sprawl: Moving Towards Sustainable Cities*; OECD Publishing: Paris, France, 2018; ISBN 978-92-64-18982-9.
34. Kemper, T.; Corban, C.; Ehlrich, D.; Florczyk, A.; Carneiro Freire, S.M.; Maffenini, L.; Melchiorri, M.; Politis, P.; Schiavina, M.; Pesaresi, M.; et al. *GHS Built-up Grid, Derived from LANDSAT, Multitemporal (1975, 1990, 2000, 2014), IR2017 V1.0—EU Science Hub—European Commission*; European Commission, Joint Research Centre (JRC): Bruxelles, Belgium, 2017.
35. Karl, T.R.; Diaz, H.F.; Kukla, G. Urbanization: Its Detection and Effect in the United States Climate Record. *J. Clim.* **1988**, *1*, 1099–1123. [CrossRef]
36. Bian, T.; Ren, G. Reassessment of urbanization effect on surface air temperature trends at an urban station of North China. *Meteorol. Atmos. Phys.* **2017**, *129*. [CrossRef]
37. Wang, C.; Wang, Z.H. Projecting population growth as a dynamic measure of regional urban warming. *Sustain. Cities Soc.* **2017**, *32*, 357–365. [CrossRef]
38. Hu, X.; Zhou, W.; Qian, Y.; Yu, W. Urban expansion and local land-cover change both significantly contribute to urban warming, but their relative importance changes over time. *Landsc. Ecol.* **2017**, *32*, 763–780. [CrossRef]
39. Squires, G.D. *Urban Sprawl: Causes, Consequences, & Policy Responses*; The Urban Insitute Press: Washington, DC, USA, 2002; ISBN 978-0-87766-709-4.
40. Cárdenas Rodríguez, M.; Dupont-Courtade, L.; Oueslati, W. Air pollution and urban structure linkages: Evidence from European cities. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1–9. [CrossRef]
41. Cho, H.S.; Choi, M.J. Effects of Compact Urban Development on Air Pollution: Empirical Evidence from Korea. *Sustainability* **2014**, *6*, 5968–5982. [CrossRef]