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DELINEATION OF METROPOLITAN AREAS IN POLAND: A FUNCTIONAL APPROACH

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ABSTRACT. Delineation of urban functional areas helps policymakers and urban planners understand the connections between the core cities and areas surrounding them, and subsequently develop policies and solutions that can serve local populations. This article develops a readily applicable econometric method for delineation that considers functional aspects of cities and their surroundings. We perform delineation analysis using the data for 78 Polish core cities, grouping them by population size. Using the satellite data on lights emitted at night, population density, commuter numbers as well as the number of houses and apartments built in each commune, we apply a threshold regression model to determine the boundaries of functional urban areas. Our main results suggest that the mean radius of functional urban areas (FUAs) around the largest (most populous) cities is, on average, 21 km, while it is between 13 and 16 km for smaller cities. We then test how the econometric results compare with the perceptions of local inhabitants through a citizen science project (CSP) conducted as a robustness check.

Keywords: Poland, urban functional areas, core city, delineation, night-lights.

Introduction

Suburbanization (city sprawl) and city shrinkage are symptoms of a continuous process of redefining the functional boundaries of cities. Various research methods have been used to cope with the delineation of urban and metropolitan areas. Some of the recent works explored such approaches as Synthetic Aperture Radar (SAR) interferometry (Esch et. al, 2014; Hoffmann et al., 2017), clusters of census tracts and adaptation of the Urban Morphological Zones methodology for smaller size cities (Nicolau & Cavaco, 2018), and in the case of metropolitan area delineation processing data on commuting patterns, mobile phone location and usage, residential suburban zones and average time spent in the city by local populations (Ouředníček et al., 2018). Delineation studies have been dominated by geographers and urban planners, leaving behind economists and their applied methods. However, the economists' rich toolkit of quantitative methods as well as the significant role that economic factors play in the city-forming processes mean that economists and economics as a discipline bring a valuable contribution to delineating boundaries of urban areas. This article is a step towards bridging that gap by applying econometric methods rooted in economic theory to identify boundaries of Polish functional urban areas (FUAs) based on their urban functions. The main research question tackled in this article is what is the dimension of FUAs in Poland and whether it varies with the core city's size. Additionally, we demonstrate how the threshold regression analysis can be implemented to delineate FUAs and argue that this relatively straightforward analytical method could be readily applied in various contexts and locations beyond Poland.

According to the gravity model (Wilson, 2011; Karlqvist & Marksjö, 1971), core cities have stronger ties with nearby communes[1] or areas than those that are located at greater distances. Therefore, we hypothesize that a determinate boundary (distance, area, zone) exists within which the functional connections of the core city with nearby communes are significantly stronger than with other, more distant, areas, forming an agglomeration or metropolitan zone. The main purpose of this article is to determine the boundaries of metropolitan areas in Poland. The sheer geographical distance is not enough to explain the ties between city cores and surrounding areas. Economic and social variables also contribute to the formation of metropolitan areas. This gives a rise to our next hypothesis that different city functions play a role in city-forming processes and that depending on the function the reach of metropolitan areas may be different. For example, the extent of a metropolitan area may be smaller if its boundary is determined by population density, while it may be larger if one takes into account commuting patterns from the outskirts to the core. Consequently, a boundary of an FUA has to be determined by taking into account a variety of socio-economic variables. Finally, we expect that the extent of a metropolitan area also depends on the rank or population size of the core city as larger cities tend to attract both the human and financial capital from a greater distance compared to smaller cities. Summing up, our main research hypotheses of this paper are: the boundaries of functional urban areas depend on socio-economic characteristics of the core cities and the neighbouring communes; and the larger the core city, the larger its functional urban area is.

The main estimation method we use is the threshold regression model that allows for an easy to apply and interpret way of delineating FUAs. Our results suggest that the larger the core city's population, the larger the distance between its core and the limits of its metropolitan functional area. The average distance of city sprawl in Poland is between 21 km for the larger cities (with more than 500 thousand inhabitants) and 13 km for small cities (with less than 70 thousand inhabitants). These results are confirmed not only by the statistical and econometric methods but also by the perceptions of residents revealed in a citizen science project (CSP) aimed at validating our desk-based econometric results. An online CSP was conducted in which residents of Łódź and its surrounding areas were directly involved in delineating the boundaries of their metropolitan area (for more details, see Bedessem, Gawronska-Nowak & Lis, 2021). A Facebook campaign was run to recruit participants within a 35 km radius of the centre of the core city which during its two waves recruited, respectively, 174 and 164 citizen scientists. They took part in a survey, commented and co-authored posts, and created a map of Łódź's FUA. The results of the CSP are consistent with our main econometric findings.

[1] Throughout this article we interchangeably use the words "commune" and "gmina" (in Polish) to denote the principal unit of administrative division in Poland.

One of the main contributions of this paper is its geographical focus as our results improve the understanding of the urbanization patterns in Poland but also could be readily generalized to other Central and Eastern European (CEE) countries. Having undergone the transition from centrally planned to market economies in the early 1990s and subsequently having joined the EU, countries such as Poland, Hungary, Slovakia, Bulgaria, Czechia and others have a lot in common when it comes to their urbanization patterns (Young & Kaczmarek, 2008; Pickles, 2010; Barnfield, 2016; Ehrlich et al, 2018; Garcia-Allon, 2018). All of them have experienced rapid suburbanization since the early- to mid-2000s and continue to follow urbanization patterns that Western European countries went through a long time ago. In that context, the CEE countries are often referred to as 'latecomers' in the urbanization literature (Bohle, 2002; Tolle, 2016;). Given that urbanization processes are similar across the CEE countries, our study of the Polish FUAs and their boundaries contributes to the understanding of the delineation patterns in other countries in the region.

In the more specific Polish context, all the efforts to date to delineate metropolitan areas have been based on descriptive or case study approaches (e.g., Swianiewicz & Klimska 2005, Gorzelak et al. 2009, Herbst & Wójcik 2013, Śleszyński 2013, Kudłacz & Markowski 2017, Komornicki et al. 2019). In contrast, our method is based on the latest trends in quantitative analysis of boundaries of FUAs such as the use of satellite imagery of night lights and commuting patterns in conjunction with modern econometric techniques such as the threshold regression approach.

Finally, this article contributes to the literature on delineation by not only proposing a readily applicable methodology but also by using a CSP to verify the statistical-data-driven results. The involvement of local inhabitants as citizen scientists in the delineation process offers an interesting extension to our research as well as a robustness check of whether the statistical results hold in a real-life setting and reflect the perception and experiences of people living in the studied areas.

The remainder of this article is structured as follows. First, we discuss the main literature on urban delineation. Second, we highlight the most important methodological considerations and describe the data used in this study. Then, we discuss the main results of the paper and confront them with the results from the linked citizen science project. Finally, we make conclusions and recommendations.

1. Literature review

This article builds on and contributes to several strands of literature on the delineation of urban areas. The first such strand is the research that uses geospatial data, including images of night lights and daytime activity registered by satellites for delineation purposes. Ch, Martin and Vargas (2021) use the night lights data to measure global urbanization rates and urban densities for cities with populations of more than 50 thousand inhabitants. They find that urban densities are higher in developing countries, while the average urban areas tend to be larger in the developed world. Moreno-Monroy, Schiavian and Veneri (2021) use the night light data and travel times between core cities and adjacent locations to delineate metropolitan areas. They assume that functional urban areas consist of a densely populated core and surrounding areas that are closely related to the centre through significantly large commuter flows. The authors consider urban areas in 31 EU and OECD countries and conclude that there is a growing trend in the concentration of urban population. Other studies use the night lights data to delineate metropolitan areas in specific countries rather than worldwide. For example, Dingel, Miscio and Davis (2021) use satellite images of night skies to determine metropolitan areas of India, China and Brazil; Harari (2020) does it for India; Tselios, Stathakis and Faraslis (2020) – for

Europe; Ellis and Roberts (2016) – for South Asia. All those articles agree that the satellite images of night lights are a good proxy for economic activity in delineating urban areas and are especially useful in the developing country context where other high quality economic data are not available. Changes in the intensity of night lights have been shown to act as a reliable proxy for localized economic activity, including expansion of various types of infrastructure and human presence, and thus, act as a good indicator of the extent of urbanized space. In countries that have been undergoing a rapid economic and technological transformation, such as Poland, using high-resolution images of night lights to delineate urban areas appears to be an attractive and dynamic approach that allows researchers to capture developmental changes in nearly real-time and at a fairly high degree of precision.

Baragwanath et al. (2021) suggest daytime satellite imagery as another source of satellite data that can contribute greatly to delineation efforts. They show that in India daytime data is a better proxy for economic activity than the night lights as the former capture more urban population and activity in local markets. Using machine learning algorithms and daytime satellite imagery, Ackermann et al. (2020) also conclude that such data is a reliable proxy for economic activity.

The second strand comprises the literature that uses data on daily commuting patterns for delineation purposes. Andersen (2002), Roca Cladera et al. (2009), Kraft, Halás and Vančura (2014), Duranton (2015), and Bosker, Park and Roberts (2021) examine commuting patterns to understand different urbanization issues such as urban sprawl, detection of metropolitan and suburban centres, and connections between functional and administrative areas. Thus, they show that commuting patterns data are essential in establishing real boundaries of urban agglomerations.

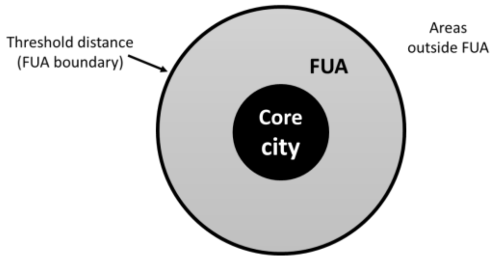
The third strand concerns the growing body of research that uses data harvested through social media in delineation studies. Chen et al. (2017) use the Tencent data, one of the largest online social media platforms in China with over 800 million users, to delineate FUAs using smartphone geo-locations of users. The authors find that this kind of data reflects well the heterogeneity of FUAs and can be used to draw the boundaries of those areas. Sun et al. (2015) also use social media to delineate functional urban areas of Berlin, Munich and Cologne. The authors collect information on the social media "check-ins" and conclude that this type of location-based (LBSN), georeferenced and timestamped data is very well suited for approximating user mobility.

Other variables frequently used in the academic literature to delineate FUAs include population density (e.g., Muniz, Galindo & Garcia, 2003), number of businesses (e.g., Fan, Qin & Kang, 2018; Huang, 2016) and capital flows (Liu, Dong & Chi, 2010). This study also uses these variables to make it comparable to the existing literature as well as test the robustness of our empirical results.

2. Methodological approach

Our methodological approach is based on a generalized econometric model and is firmly rooted in economic theory. It sees a metropolitan area as an organism determined by functional and economic relations and interlinkages among agents concentrated within a discrete geographical space. The concentration of economic activity within that space is driven by the economies of scale and agglomeration effects that allow monetary and non-monetary cost savings and therefore promote the creation of wealth and economic growth of the area based on innovation, industrial specialization, and better access to human and financial capital. We expect these processes to play a pivotal role, aside from physical and geographical factors, in determining the spatial extent of a metropolitan area by fuelling its expansion, although we expect this effect to be decaying in distance from the city core.

Thus, in this article we delineate FUAs which represent a set of self-contained, cohesive and spatially continuous markets that consist of suppliers and buyers, or recipients, of goods and services, for example, the housing, job, transport or public services markets (see Bertaud, 2018; Martinez-Bernabeu et al., 2012). The emphasis on self-containment and spatial continuity can be operationalized by the gravity model mentioned in the previous section and also studied in Moreno-Monroy et al. (2021), Wilson (2011) and Karlqvist and Marksjö (1971). In simple terms, a boundary exists beyond which the market or functional cohesion fades and places beyond that boundary can no longer be considered parts of the metropolitan area. This is also consistent with Tobler's first law of geography according to which closer areas have stronger connections than areas located further away (Tobler, 1970).



Graph 1. Gravity model: the core city, functional urban area (FUA) and its boundary
Source: *own compilation*

Graph 1 graphically summarises the conceptual approach of the gravity model. The urban core is expected to be connected by stronger ties of interdependence with surrounding and nearby areas than with other, more distant locations. Therefore, it follows that a certain boundary or threshold distance exists within which the functional ties between the core city and its surroundings are strong enough to create a concise metropolitan space and beyond which the intensity and importance of these ties decrease significantly. We use regression analysis to determine this boundary by estimating the threshold distance from the core city's centre within which the functional linkages among localities are statistically significantly stronger than beyond that threshold. Although *Graph 1* is relevant to a monocentric metropolitan area with a single city core, the gravity approach can also be extended to polycentric metropolitan areas or agglomerations, as we demonstrate in the following empirical section.

The core city fulfils a range of cultural, educational, economic and administrative functions whose spatial extent is not likely to be uniform and instead vary depending on the type of the function and underlying socio-economic processes. For example, the core is likely to have a stronger influence on the density of residential buildings within its immediate vicinity than farther afield. Typically, we observe taller multiple occupancy buildings in close proximity to the city centre, with a relatively high number of residents per square kilometre. Moving further away from the centre, the buildings tend to become smaller, with fewer residents and the population density is likely to decline at a relatively high rate (although still remain higher than outside the metropolitan area). However, we expect economic and business ties to have a much further reach as the core city is likely to be a key destination for employment and commercial purposes for individuals living even in further and less densely populated areas. Thus, we expect the spatial extent of a metropolitan area to vary depending on which functional linkages are considered. Following our example, if we focus only on a single factor such as population density we are likely to obtain relatively small metropolitan areas, whereas considering economic ties such as commuting patterns, we are likely to observe relatively larger metropolitan areas. That intuition is tested in our empirical exercise using several measures of various urban functions.

Finally, we expect the spatial reach of a metropolitan area, or the extent of the threshold distance, to depend on the size of the core city. Larger cities are expected to have larger gravitational pull and thus should be characterized by further-reaching influence and connections than medium-sized and small cities. Therefore, in the ensuing empirical analysis, we divide Polish urban cores into categories based on their population size.

We operationalize the above gravity model using econometric regression methods to estimate the threshold distances that mark the boundaries of the Polish metropolitan areas. Those distances indicate how far the boundaries of metropolitan areas lie from the centroids of the core cities. Like all econometric models, our method and empirical results constitute a generalization or simplification of reality that offers both descriptive and predictive lessons in understanding the processes that form metropolitan areas. Their reliability tends to increase in the used sample size. Since the values of threshold distances may be relatively small, especially for smaller core cities, and therefore include only a few communes, applying the threshold regression to an individual city would likely give unreliable results. To assuage this risk, we group our cities into seven clusters depending on their population size (see the Data section). This way, every regression is run on a sample of sufficient size that ensures reliability and efficiency of estimates and allows us to consider relatively small threshold values. Consequently, an important caveat must be made that our estimations are not city-specific but rather represent averaged values for metropolitan areas surrounding core cities belonging to a particular population size-based grouping

We begin with the threshold regression analysis which estimates the threshold distance within which the functional relations between the core city and surrounding areas are statistically significantly stronger than between the core city and areas located beyond that threshold. Following this method, we identify metropolitan areas that comprise places located at a distance not greater than the estimated threshold from the core city's centroid.

In practice, this approach requires an estimation of two econometric models that describe the functional relations between the same set of variables for locations within a metropolitan area and locations situated outside of such an area. The regression coefficients are expected to take statistically significantly different values on both sides of the estimated threshold, reflecting the shift in the strength and nature of linkages of locations on either side of the threshold with the core city. The threshold regression method was pioneered by Hansen (1999, 2017) and in our case can be written as:

$$y_i = \alpha_k + \beta_k' x_i + \gamma_k' z_j + \epsilon_i = \begin{cases} \alpha_1 + \beta_1' x_i + \gamma_1' z_j + \epsilon_i \text{ if } q_i \leq c \\ \alpha_2 + \beta_2' x_i + \gamma_2' z_j + \epsilon_i \text{ if } q_i > c \end{cases}$$

where i indicates a commune or gmina, y_i is the dependent variable, α_k is a constant, x_i and z_j represent explanatory variables for a commune i or the nearest core city j[2], respectively. ε_i is the error term. The dependent variables used in the research are the number of regular commuters to the core city, population density, the average intensity of light emitted at night by the communes, and the number of newly built residential apartments per 1000 inhabitants. The vector of commune level explanatory variables, x_i, includes: the distance from the nearest core city to the commune measured in kilometres, population density, population size, the average intensity of light emitted at night by the communes, and the number of newly built residential

[2] Each commune i is assigned to a potential metropolitan area on the basis of the geographic distance to the nearest core city j.

apartments per 1000 inhabitants. The specific commune level variables are used in the model either as a dependent or independent variables, and never as both in the same regression. For example, if population density is used as the dependent variable, it is then omitted on the right-hand side of the regression and is not used as an explanatory variable. The same rule applies to other variables. The vector of core city explanatory variables, z_j, includes: population size, population density, the number of newly built residential apartments per 1000 inhabitants, and the number of businesses per 1000 inhabitants. The used variables are presented in more detail in the following section. The model allows regression coefficients to take different values depending on the threshold value q_i that represents the distance from core city j in kilometres. The value of that threshold is not known a priori and the technique requires that the estimation is repeated for all potential threshold values. Consequently, a single threshold value c is chosen for which the model achieves the best goodness of fit[3]. That threshold distance c is an estimate of the distance between the core city's centroid and its metropolitan area's boundary.

3. Data

We perform the delineation analysis using the data for 78 Polish core cities which together form 59 monocentric and 3 polycentric metropolitan areas (see Appendix *Table A.1* for the full list). We group the core cities based on their population size and get seven main groups as shown in *Table 1*. As previously explained, our analysis is performed on groups of communes surrounding core cities in each group and not on an individual city level to ensure sufficient sample sizes and reliable estimates in the regression analysis. Working on the city groupings has the distinctive advantage of shedding light on common or shared patterns that drive urbanization processes around large, medium and small size cities.

The data on population size, population density, number of businesses per 1000 inhabitants, per capita income, number of regular commuters to the core city, and number of newly built residential apartments per 1000 inhabitants are taken from Statistics Poland Local Data Bank[4]. All variables are represented on the commune (gmina) level. Given that we require a relatively low granularity of the data as well as comparability across all 2,478 communes in Poland, we use the data collected in the last available Polish census that took place in 2011[5].

We complement our dataset by adding the data for the average intensity of light emitted at night by the cities and communes. High-resolution satellite images showing a measure of the intensity of light observed at night are collected by the U.S. Air Force Weather Agency since 1992 and published by NOAA National Geophysical Data Center (2017). This variable records the annual average light intensities and is free of the influence of natural phenomena (e.g., fires or cloud cover). We use this variable as a proxy for the level of development and wealth of communes, following Ghosh et al. (2010), Henderson et al. (2012), Lowe (2014) and Storeygard (2016). Additionally, this variable is a proxy for the presence of human settlements and population density. Values for the night lights variable range between 0 and 64, with low values occurring in unlit spaces characterized by a low level of human or economic activity. High values, on the other hand, suggest that communes are relatively more economically developed. Descriptive statistics of the main variables used in the analysis can be found in Appendix *Table A.2*.

[3] The method requires data trimming which ensures that there is a sufficient number of observations on each side of the hypotesised threshold to perform regression analysis. We decide for 10% data trimming which means that at least 10% of all communes are considered on either side of the threshold c.
[4] https://bdl.stat.gov.pl/BDL/start
[5] The full data from the 2021 census has not been published yet and is expected to be published in September 2023.

According to *Table 1*, more than 13.6 million people or 35% of Poland's population live in the 78 Polish core cities. The largest city, Warsaw, has nearly 2 million inhabitants, the other large cities, Kraków, Poznań, Wrocław and Łódź, have populations between 500 and 800 thousand. The significantly larger size of the capital and its status as the national administrative and business hub may mean that city-forming processes and metropolitan 'spillovers' involving Warsaw follow patterns different from that of the other four large cities. Therefore, we consider two cases or sub-samples of cities with more than 500 thousand inhabitants: including Warsaw and excluding Warsaw. Not surprisingly, average population density is the highest in the biggest cities and then decreases as the cities' populations get smaller. Similar trends can be observed also in the other economic variables in *Table 1*. For example, the five most populous cities have 60% more firms per 1000 inhabitants than the core cities with less than 100 thousand residents. The average income per capita in the top-five largest cities is 43% higher than in the cities from the smallest population group. The 23 cities with populations above 150 thousand attract 62% of all Polish commuters from non-city areas. One-third of all commuters appear to work in the top five cities that offer the highest per capita income and have the highest concentration of economic activity. Finally, as expected, the core cities are characterized by higher levels of economic activity, measured by the number of firms, per capita income, the building of new apartments and night lights, than the rest of the country. This suggests that Poland's main economic activity is concentrated in the core cities.

Graph 2 shows the distribution of our main variables used in the analysis by distance from the nearest core city. Most of the charts show decreases in the values of the variables as the distance from core cities increases, confirming the legitimacy of their use for delineating functional urban areas. The negative correlation between our main variables and the distance to the core cities becomes smaller with the size of the core cities – the slopes of the red lines on the charts show that the correlation becomes weaker as we move from the large to small city categories. This seems to be the case for all the analyzed variables and suggests that larger cities have higher levels of concentration of economic activity and people if compared to smaller cities. This is consistent with the already mentioned gravity model and the Newtonian principle that larger objects have a larger gravitational pull.

4. Conducting research and results

4.1. The spatial extent of Polish FUAs

The method we use to estimate the spatial extent of metropolitan areas for the seven city-size clusters presented in the previous section is the threshold regression model[6]. The full set of regression estimates for each core city grouping can be found in Appendix *Tables A.3* through A.9. The summary results in *Table 2* show that the average threshold distance ranges between approximately 21 km and 13.5 km for the largest and the smallest cities, respectively. The results differ depending on the measure used to calculate the span of the FUA which is in line with our assumptions and supports the hypothesis that the functional areas around the cities are formed based on a variety of different connections between the cores and the areas around them. Therefore, one cannot use only one variable to delineate the FUA but rather use a combination of different variables to arrive at the final result.

[6] When searching for the threshold distances, we impose a restriction of maximum of 50 km. As can be seen in Table 2, this should not affect our results as all estimates are well below the 50 km value. The average distance between two closest core cities is 46.6 km The largest distance between a commune and its nearest core city is 78 km.

The last column of *Table 2* shows the synthesized threshold which envelopes all the other four functional measures by imposing them onto each other. This means that we select the largest of the FUAs calculated based on the number of commuters, population density, economic activity, and the built apartments. The synthesized threshold, therefore, shows the largest extent of a metropolitan area. The larger the core city, the larger its FUA tends to be. The only exception is found for cities of 250-500 thousand inhabitants and appears to be driven by the local commuting patterns and the characteristics of the local economies surrounding core cities within this category. Communes surrounding the largest cities (above half a million inhabitants) tend to have a better employment offer that, to some significant extent, satisfies the employment needs of their own inhabitants and those of surrounding communes. In contrast, areas surrounding but located outside of the core cities with 250 to 500 thousand inhabitants, such as Białystok, Lublin, Bydgoszcz and Szczecin, tend to have relatively less vibrant and poorer employment markets compelling their inhabitants to commute to the core cities for work or education.

Table 2. The FUAs spread in kilometres – the threshold regression estimates

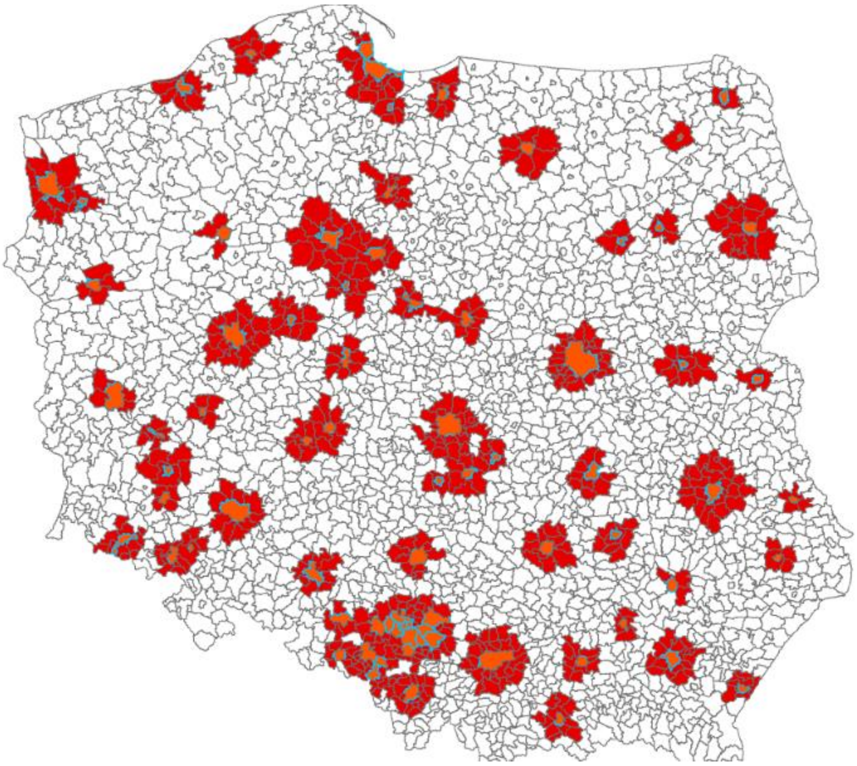
Core cities, ths. inhabitants	Commuters	Population density	Economic activity (night lights)	Built apartments	Average	Synthesized threshold
> 500	24.96	14.38	24.82	18.88	20.76	24.96
> 500, no Warsaw	24.82	18.32	17.9	18.83	19.97	24.82
250 – 500	27.19	16.21	17.2	19.79	20.10	27.19
150 – 250	18.24	16.48	15.78	15.62	16.53	18.24
100 – 150	15.48	14.47	18.44	13.15	15.39	18.44
70 - 100	17.18	16.48	16.48	14.33	16.12	17.18
< 70	11.6	16.44	14.98	10.77	13.45	16.44

Notes: Synthesized threshold column contains the largest values of threshold estimates for a given city size chosen from the 'Commuters', 'Population density', 'Economic activity (night lights)', and 'Built apartments' categories.
Source: *own compilation*.

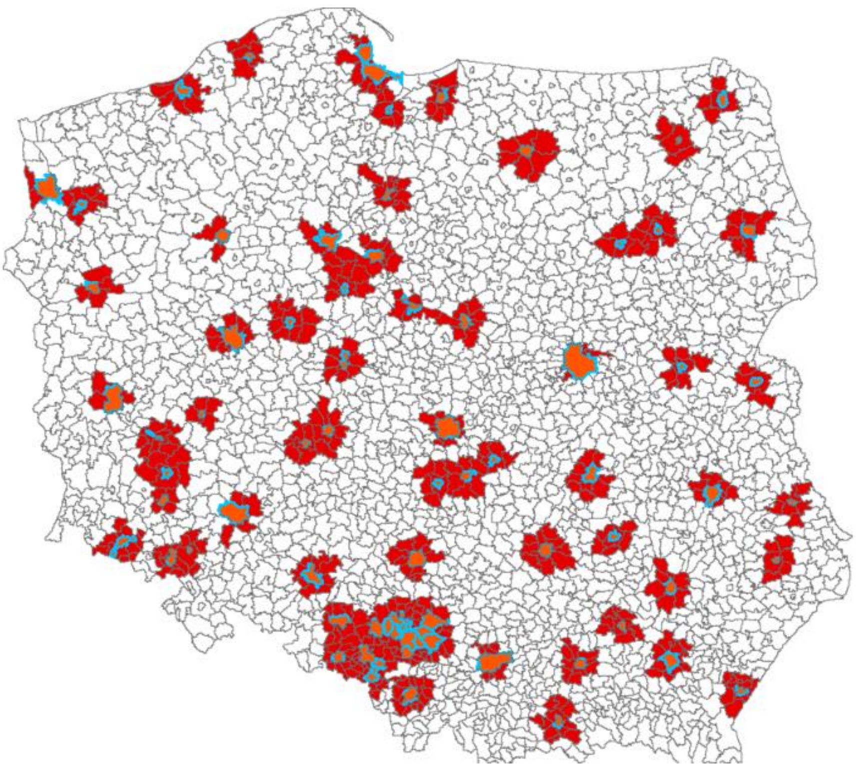
Graphs 3 through *6* illustrate the results of our delineation analysis based on the four functional measures. *Graph 7* shows FUAs using the average of the four measures (commuters, population density, economic activity and built apartments), whereas *Graph 8* presents the FUAs based on the synthesized threshold.

4.2. The Citizen Science Project (CSP) as a robustness check

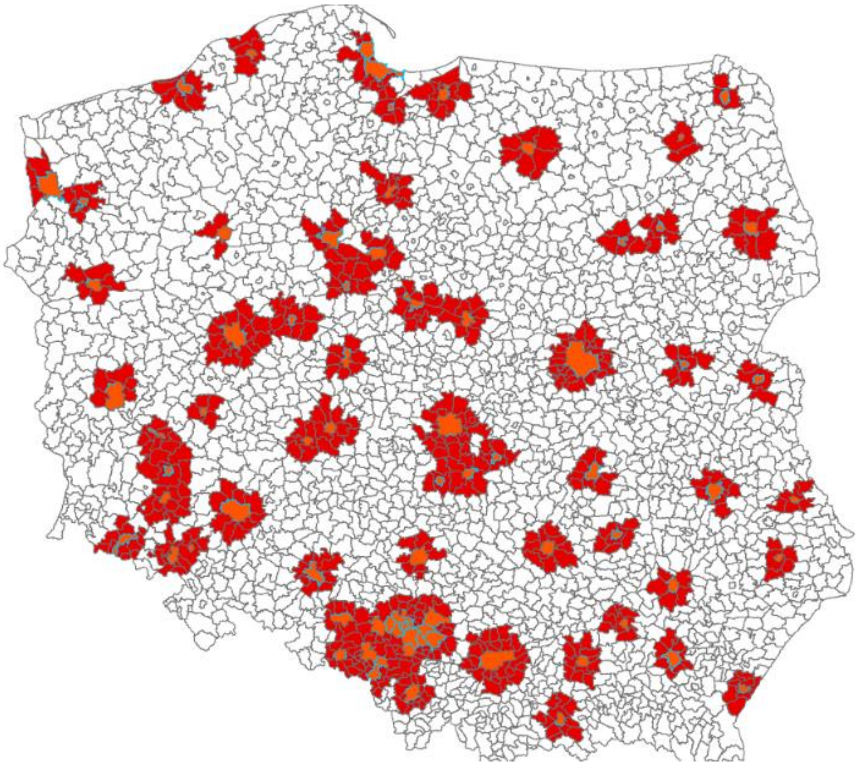
Citizen Science (CS) is a research method that actively involves 'lay citizens' (in our case, residents) in a research project. This direct involvement allows 'citizen scientists' to work alongside professional researchers, co-implement research activities and to co-create knowledge. The general concept of CS refers to a large diversity of forms of participation for all of those who are not professional researchers (individual citizens, NGOs, groups of patients, etc.) in the production of scientific knowledge (Eitzel, Cappadonna, Santos-Lang, Duerr, et al. 2017; Cooper & Lewenstein 2016). Moreover, it is considered one of the most effective methods of gaining public trust in scientific results (Bedessem, Gawronska-Nowak & Lis, 2021).



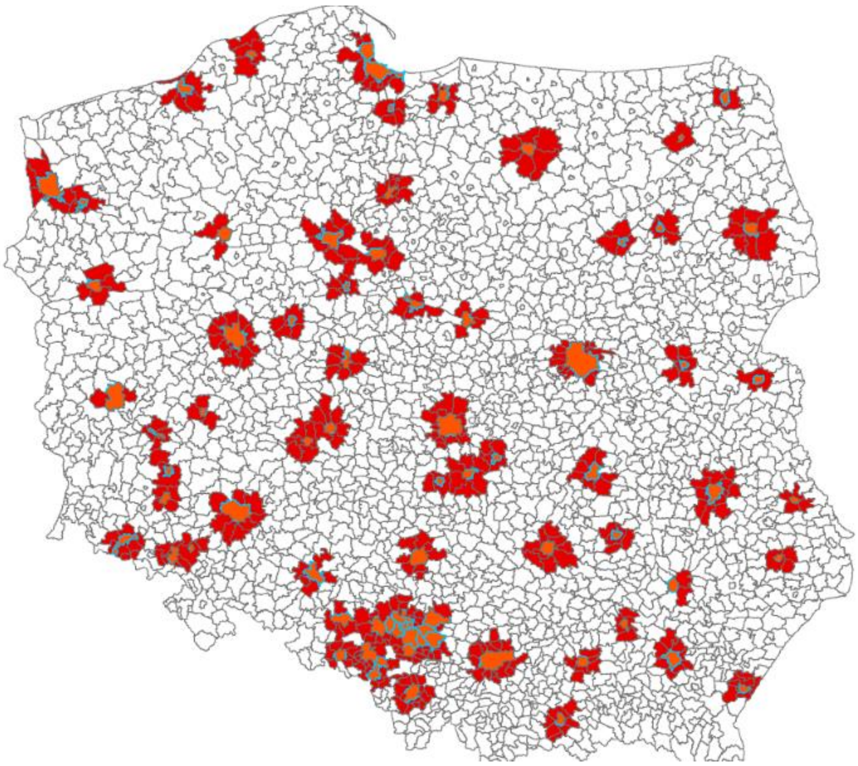
Graph 3. FUAs based on the number of commuters.
Source: *own compilations.*



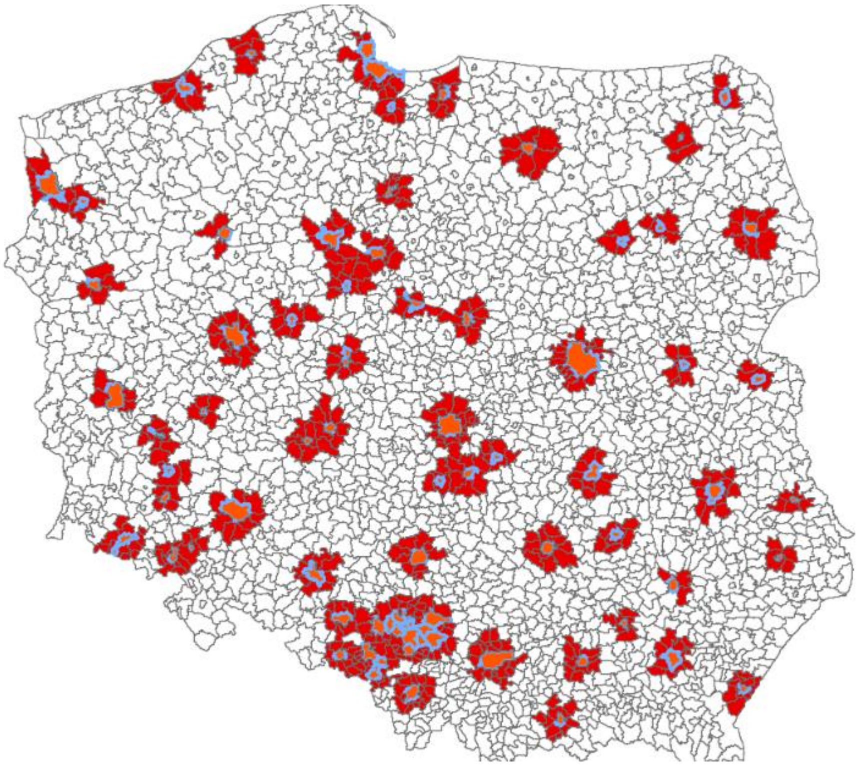
Graph 4. FUAs based on population density.
Source: *own compilations.*



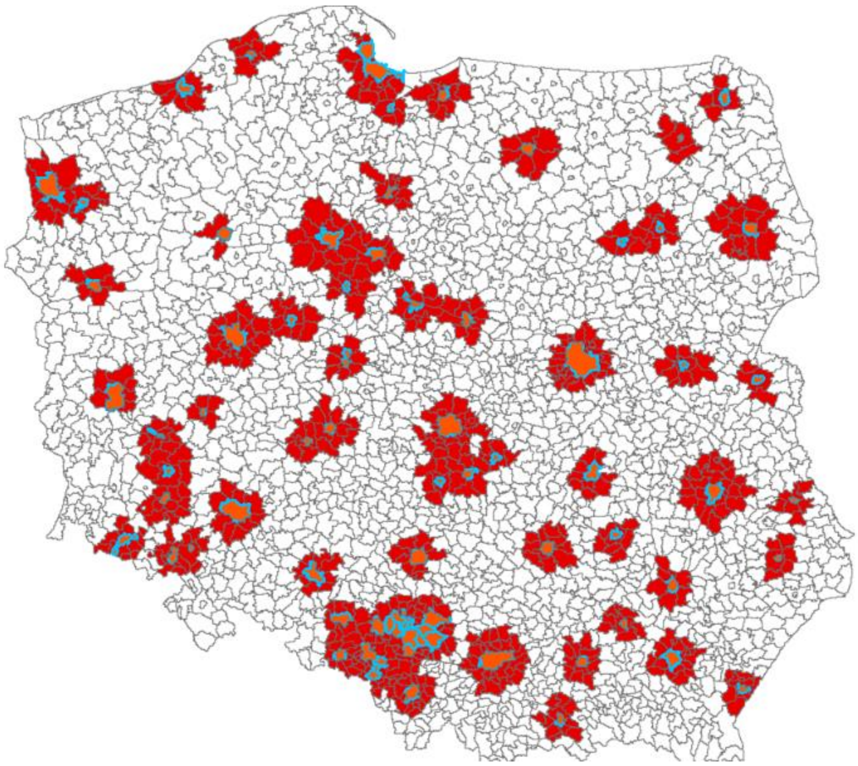
Graph 5. FUAs based on economic activity measured by the night lights.
Source: *own compilations.*



Graph 6. FUAs based on the number of built apartments.
Source: *own compilations.*



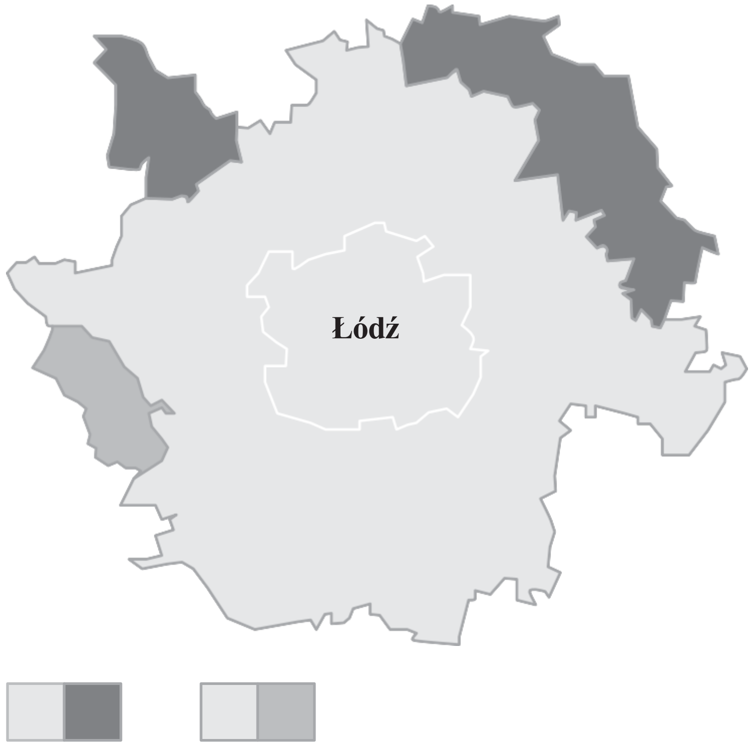
Graph 7. FUAs based on the average of the four measures (commuters, population density, economic activity, and built apartments).
Source: *own compilations.*



Graph 8. FUAs based on the synthesized threshold.
Source: *own compilations.*

In geography, CS usually takes the form of geo-crowdsourcing where citizens play the role of 'sensors' reporting geographical data in a passive way (Sui, Elwood & Goodchild, 2012). In contrast, our quasi-experimental CSP required a more active and cognitive effort from citizens who were actively involved in identifying and applying criteria relevant to delineate FUAs. The CSP is described in more detail in Bedessem, Gawronska-Nowak and Lis (2021). Here, it serves as a robustness check of the econometric results described in the previous section. It was conducted in Łódź, the country's fourth-largest city, with the population of more than 670,000 inhabitants. The city was chosen as it is one of the fastest-shrinking cities in Central and Eastern Europe (Haase et al., 2021) and the dynamic shrinking process creates an important premise for redefining its FUA.

A Facebook campaign was conducted to recruit participants into the CSP within a 35 km radius of the centre of Łódź. There were two three-week waves, attracting 338 citizen scientists, in which they were asked to delineate a map of Łódź's FUA. *Graph 9* compares the map obtained from the CSP with the map based on the econometric estimates in the earlier section. A visual inspection of *Graph 9* reveals that our econometric approach yields results that are in line with citizens' perceptions of Łódź's FUA. According to our econometric estimates, FUAs around the largest cities in Poland stretch approximately 25 km from the core cities' centres. In the case of Łódź, this includes 22 gminas. According to the SCP results, the city's FUA is slightly larger and includes 26 gminas.



a. Citizen science result (26 gminas)   b. Econometric results (22 gminas)

Graph 9. FUA of Łódź: citizen science vs. econometric results.
Notes: The lightest grey area covers gminas that were indicated as a part of Łódź's FUA both in the CSP and the econometric analysis. The medium dark grey-coloured gmina West of Łódź is included only by the econometric estimation. The darkest grey-coloured areas to the North show gminas identified only by citizen scientists.
Source: *Bedessem, Gawronska-Nowak and Lis (2021, p.312).*

Conclusion

Using data for the 78 core cities, we estimate a threshold regression model to delineate FUAs in Poland. The analysis is done on clusters of core cities split by population size. The main variables used in the estimations are the number of commuters, population density, economic activity proxied by the intensity of light emitted at night and registered by the satellites, and the number of built apartments.

The results confirm the hypothesis that larger cities have larger FUAs. Based on our synthesized threshold measure, it is estimated to spread around 25 km for the biggest Polish cities and around 16 - 18 km for the smaller ones. The average span of FUAs, based on four functional variables, is around 21 km for the largest core cities and 13-16 km for the smaller ones. Our results also support the argument that delineation should be done using a variety of socio-economic variables. The results differ depending on the type of variables measuring socio-economic conditions and linkages between the core cities and surrounding areas. This conclusion is well illustrated by the differences in the threshold regression results estimated using the population density compared to those based on the number of commuters. In the case of the former, the FUAs' extent is the smallest for the cities with more than 500 thousand inhabitants. This is explained by the high population density of the core cities in which we observe many multistory apartment buildings both in the city centre and the outskirts. In comparison, the estimates based on the number of commuters reveal the largest FUAs' expansion which could be explained by the pull of a large city with its diverse labour market and entertainment industry.

Moreover, our statistical results have been verified by the CSP conducted in Łódź. The FUA map created based on our econometric method is largely consistent with the map created by the residents of Łódź. Not only does such a robustness check support our results, but it also creates additional societal benefits of potentially increasing public trust in science.

Although the econometric approach we suggest is relatively easy to use, it has a potential weakness. It ignores spillover effects or links that exist between neighbouring geographical areas and the resulting spatial correlations that are likely to arise when measuring the same variables across nearby districts. It assumes that only the core city has a one-directional effect on the surrounding areas, ignoring the potential effects of those areas on the core city or the effects that such districts may have on their non-core neighbours. Future research should take into account the spatial correlations and the spillover effects between the neighbouring areas.

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Appendices

Table A.1. Core cities and their characteristics, 2011.

Core city name	Type of FUA	FUA name	Population	Population dencity, (ppl./km^2)	Average income per capita, zł.	Number of firms per 1000 inhbt.
Bełchatów	monocentric	bełchatowska	60222	1721	2676	87
Biała Podlaska	monocentric	bialska	58000	1184	3654	94
Białystok	monocentric	białostocka	294298	2885	4324	106
Bielsko-Biała	monocentric	bielska	174503	1396	4030	141
Bydgoszcz	monocentric	bydgoska	363020	2063	3614	118
Chełm	monocentric	chełmska	66176	1891	3621	85
Częstochowa	monocentric	częstochowska	235798	1474	3892	111
Elbląg	monocentric	elbląska	124257	1553	3890	97
Ełk	monocentric	ełcka	59274	2823	2677	84
Głogów	monocentric	głogowska	69259	1979	3033	98
Gniezno	monocentric	gnieźnieńska	70263	1714	2284	128
Gorzów Wielkopolski	monocentric	gorzowska	124554	1448	3443	143
Grudziądz	monocentric	grudziądzka	98438	1697	3986	80
Inowrocław	monocentric	inowrocławska	75938	2531	2984	91
Jelenia Góra	monocentric	jeleniogórska	83463	766	4065	148
Kalisz	monocentric	kaliska	105122	1524	3874	110
Kędzierzyn-Koźle	monocentric	kędzierzyńsko-kozielska	63974	516	3330	108
Kielce	monocentric	kielecka	201815	1835	5094	139
Konin	monocentric	konińska	78209	954	4679	104

Table A.1. cont‘d.

ISSN 2071-789X

Core city name	Type of FUA	FUA name	Population	Population dencity, (ppl./km^2)	Average income per capita, zł.	Number of firms per 1000 inhbt.
Koszalin	monocentric	koszalińska	109233	1115	3640	166
Kraków	monocentric	krakowska	759137	2322	4400	153
Legnica	monocentric	legnicka	102979	1839	3597	126
Leszno	monocentric	leszczyńska	64713	2022	4251	134
Lublin	monocentric	lubelska	348567	2371	3988	118
Lubin	monocentric	lubińska	75147	1833	3325	97
Łomża	monocentric	łomżyńska	63070	1911	4524	96
Łódź	monocentric	łódzka	725055	2475	3775	120
Mielec	monocentric	mielecka	61479	1308	2553	95
Nowy Sącz	monocentric	nowosądecka	84325	1454	4715	110
Olsztyn	monocentric	olsztyńska	175420	1993	4493	124
Opole	monocentric	opolska	122439	1262	4511	164
Ostrołęka	monocentric	ostrołęcka	53443	1843	4218	107
Ostrowiec Świętokrzyski	monocentric	ostrowiecka	73300	1593	2565	109
Ostrów Wielkopolski	monocentric	ostrowska	72907	1736	2323	121
Piła	monocentric	pilska	74818	726	2799	113
Piotrków Trybunalski	monocentric	piotrkowska	76505	1142	4113	96
Płock	monocentric	płocka	124318	1413	4902	97
Poznań	monocentric	poznańska	553564	2113	4459	180
Przemyśl	monocentric	przemyska	64728	1407	6666	91
Racibórz	monocentric	raciborska	56245	750	2540	93
Radom	monocentric	radomska	220602	1970	3974	110

ISSN 2071-789X

Table A.1. cont‘d.

Core city name	Type of FUA	FUA name	Population	Population dencity, (ppl./km^2)	Average income per capita, zł.	Number of firms per 1000 inhbt.
Rzeszów	monocentric	rzeszowska	180031	1539	3995	120
Siedlce	monocentric	siedlecka	76480	2390	4183	103
Słupsk	monocentric	słupska	95542	2222	4355	139
Stalowa Wola	monocentric	stalowowolska	64756	780	3102	96
Stargard	monocentric	stargardzka	69771	1454	2367	117
Suwałki	monocentric	suwalska	69210	1049	4107	99
Szczecin	monocentric	szczecińska	409596	1361	3375	159
Świdnica	monocentric	świdnicka	60213	2737	2528	137
Tarnów	monocentric	tarnowska	113593	1578	4264	96
Tczew	monocentric	tczewska	60809	2764	2633	94
Tomaszów Mazowiecki	monocentric	tomaszowska	65834	1567	2370	84
Toruń	monocentric	toruńska	204921	1767	4019	117
Wałbrzych od 2013	monocentric	wałbrzyska	119955	1411	2711	115
M.st.Warszawa od 2002	monocentric	warszawska	1708491	3305	6616	200
Włocławek	monocentric	włocławska	116345	1385	3890	101
Wrocław	monocentric	wrocławska	631235	2154	5558	160
Zamość	monocentric	zamojska	65784	2193	4678	117
Zielona Góra	monocentric	zielonogórska	119197	2055	3961	134
Bytom	polycentric	górnośląska	176106	2552	3858	92
Chorzów	polycentric	górnośląska	111536	3380	3604	100
Dąbrowa Górnicza	polycentric	górnośląska	125475	664	4453	95

ISSN 2071-789X

Table A.1. cont'd.

Core city name	Type of FUA	FUA name	Population	Population dencity, (ppl./km^2)	Average income per capita, zł.	Number of firms per 1000 inhbt.
Gliwice	polycentric	górnośląska	186868	1395	4249	124
Jaworzno	polycentric	górnośląska	94580	618	4295	82
Katowice	polycentric	górnośląska	309304	1875	4382	138
Mysłowice	polycentric	górnośląska	75428	1143	3070	90
Piekary Śląskie	polycentric	górnośląska	57745	1444	2812	70
Ruda Śląska	polycentric	górnośląska	143024	1834	3544	67
Siemianowice Śląskie	polycentric	górnośląska	69992	2800	3209	91
Sosnowiec	polycentric	górnośląska	215262	2366	2956	109
Świętochłowice	polycentric	górnośląska	52813	4063	2838	74
Tychy	polycentric	górnośląska	129322	1577	4491	103
Zabrze	polycentric	górnośląska	180332	2254	3506	90
Jastrzębie-Zdrój	polycentric	rybnicka	92105	1084	4011	64
Rybnik	polycentric	rybnicka	140944	952	4494	93
Żory	polycentric	rybnicka	62110	956	3545	84
Gdańsk	polycentric	trójmiejska	460517	1758	4520	142
Gdynia	polycentric	trójmiejska	248939	1844	4127	141

Source: *Statistics Poland (2021).*

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Table A.2. Descriptive statistics of the main variables used in the analysis, 2011.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Population density (ppl./km^2)	2471	223.6	473.3	4.5	4062.5
Population	2471	15569.6	50534.5	1353.0	1708491.0
Number of completed flats per 1000 inhabitants	2471	2.7	2.8	0.0	34.6
Number of firms per 1000 inhabitants	2471	72.5	31.0	27.0	361.0
Per capita income, zł.	2471	3100.6	1257.1	1966.8	44563.2
Economic activity (night lights intensity)	2471	15.4	11.9	1.0	62.0
Number of people commuting to work from a commune	2471	525.5	854.5	0.0	15323.0

Sources: *Statistics Poland (2021) and NOAA National Geophysical Data Center (2017).*

Table A.3. Threshold regression estimates for core cities of 500 thousand inhabitants or more (including Warsaw).

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	24.96		14.38		24.82		18.883	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	-16.35***	-2.2	47.96***	31.57***			-0.12*	0.13***
	(5.72)	(6.32)	(7.80)	(3.15)			(0.069)	(0.05)
Distance to core's centre	-61.65***	-10.72**	25.26	8.65***	-1.46***	-0.18***	-0.78***	-0.12***
	(11.83)	(4.54)	(44.50)	(3.20)	(0.14)	(0.065)	(0.21)	(0.03)
Population density	0.43***	0.28**			0.006***	0.013***	-0.0005	-0.003***
	(0.075)	(0.12)			(0.001)	(0.0012)	(0.0009)	(0.0008)
Population size (inhabitants)	0.06***	0.039***	0.01**	0.01***	0.00009**	0.0002***	-0.00005	0.00003
	(0.003)	(0.0045)	(0.005)	(0.003)	(0.00004)	(0.00006)	(0.00004)	(0.00003)
Built apartments	2.93	-3.72	-0.32	-28.44***	-0.1	0.62***		
	(7.26)	(13.87)	(9.46)	(7.60)	(0.11)	(0.20)		
Variables measured at core city								
Population density	21.07***	-2.24	-8.46	-3.51	0.17***	0.07	-0.07	-0.04
	(4.43)	(3.09)	(6.63)	(2.61)	(0.06)	(0.05)	(0.05)	(0.03)
Population size (inhabitants)	-0.023***	0.003	0.009	0.004	-0.0002**	-0.00007	0.00008	0.00004
	(0.005)	(0.003)	(0.007)	(0.003)	(0.00007)	(0.00005)	(0.00005)	(0.00003)
Number of businesses[a]	43.45***	-1.95	-9.96	-5.49	0.33***	0.08	0.062	-0.02
	(7.45)	(5.30)	(10.92)	(4.49)	(0.11)	(0..08)	(0.08)	(0.05)
Built apartments	739.21***	-79.95	-325.58	-126.3	5.42**	2.34	-3.21*	-1.57
	(151.77)	(108.12)	(235.35)	(90.26)	(2.23)	(1.60)	(1.69)	(0.97)
costant	-41022.72***	4259.44	14220.36	6349.36	-307.19**	-125.35	148.74	74.7
	(8588.41)	(6010.5)	(12995.6)	(5091.24)	(125.75)	(88.76)	(93.86)	(54.97)
N	256		256		256		256	
BIC	3084.14		3062.37		921.42		711.29	
HQIC	3041.76		3024.22		883.27		673.14	

Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table A.4. Threshold regression estimates for core cities of 500 thousand inhabitants or more excluding Warsaw.

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	24.82		18.32		17.899		18.83	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	-10.13	-3.11	25.68***	38.17***			-0.05	0.1
	(7.82)	(10.28)	(4.07)	(2.78)			(0.08)	(0.09)
Distance to core's centre	-90.00***	-9.46**	6.34	3.54	-1.71***	-0.099**	-0.63***	-0.10***
	(15.40)	(4.74)	(13.93)	(2.21)	(0.27)	(0.048)	(0.23)	(0.04)
Population density	-0.42**	0.15			0.012***	0.019***	-0.005***	-0.002
	(0.18)	(0.23)			(0.002)	(0.0014)	(0.0018)	(0.002)
Population size (inhabitants)	0.07***	0.03***	0.011***	-0.003	0	0.0002***	0	0.00006
	(0.0038)	(0.006)	(0.002)	(0.003)	(0.00005)	(0.00005)	(00004)	(0.00004)
Built apartments	-18.86**	2.49	-13.13***	-13.89	-0.05	0.27		
	(8.61)	(21.64)	(5.06)	(9.17)	(0.12(	(0.19)		
Variables measured at core city								
Population density	7.20***	-0.89	-20.09	-16.14	1.46***	0.27	0.24	-0.09
	(1.39)	(0.97)	(19.55)	(11.14)	(0.41)	(0.25)	(0.34)	(0.20)
Population size (inhabitants)	-0.002**	0.0003	0.03	0.023	-0.0021***	-0.0004	-0.0004	0.0001
	(0.0009)	(0.0006)	(0.03)	(0.016)	(0.0006)	(0.0004)	(0.0005)	(0.0003)
Number of businesses[a]	51.94***	-3.29						
	(7.35)	(5.11)						
Built apartments			-975.34	-757.64	69.15***	12.74	12.17	-4.16
			(927.45)	(528.27)	(19.40)	(11.64)	(15.97)	(9.32)
Costant	-20964.9***	2648.2	30814.98	24483.65	-2185.99***	-417.32	-323.29	144.8
	(3806.6)	(2664.8)	(29767.3)	(17007.1)	(624.27)	(374.71)	(512.94)	(299.87)
N	175		175		175		175	
BIC	2076.99		1867.81		533.05		449.55	
HQIC	2039.37		1833.95		499.19		415.69	

Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table A.5. Threshold regression estimates for core cities of 250 to 500 thousand inhabitants.

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	27.19		16.207		17.2		19.788	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	5.66	-3.25	25.72***	33.67***			0.15	0.09
	(4.08)	(6.24)	(4.88)	(2.00)			(0.12)	(0.09)
Distance to core's centre	-37.80***	-6.99***	37.25***	3.76***	-1.32***	-0.10***	-0.71***	-0.015
	(3.47)	(2.15)	(13.70)	(1.14)	(0.22)	(0.03)	(0.17)	(0.026)
Population density	-0.009	-0.07			0.015***	0.02***	-0.003	-0.002
	(0.09)	(0.17)			(0.002)	(0.0014)	(0.002)	(0.002)
Population size (inhabitants)	0.04***	0.02***	0.03***	-0.002	0.00009	0.0002***	-0.0003***	0.00002
	(0.002)	(0.003)	(0.005)	(0.002)	(0.0001)	(0.00004)	(0.00007)	(0.00004)
Built apartments	6.998	-0.77	-11.32**	-7.32	0.11	0.41**		
	(4.55)	(11.42)	(5.79)	(6.46)	(0.14)	(0.196)		
Variables measured at core city								
Population density	0.095	0.23	-0.46	-0.79***	0.03***	0.03***	-0.02***	-0.0005
	(0.26)	(0.26)	(0.35)	(0.14)	(0.007)	(0.003)	(0.007)	(0.004)
Population size (inhabitants)	0.005*	0.003	-0.005	-0.0095***	0.00042***	0.0003***	-0.0001	0
	(0.003)	(0.003)	(0.005)	(0.0018)	(0.00009)	(0.00004)	(0.00009)	(0.00005)
Number of businesses[a]	-14.73***	0.19						
	(2.54)	(3.14)						
Built apartments			47.93*	-13.56	-0.16	0.57*	1.69***	-0.24
			(27.94)	(12.87)	(0.63)	(0.34)	(0.44)	(0.29)
costant	675.82	-1255.4	1649.24	4824.02***	-185.42***	-169.71***	94.56**	6.62
	(1689.6)	(1671.04)	(2414.5)	(959.5)	(49.33)	(21.30)	(43.73)	(23.80)
N	130		132		132		132	
BIC	1275.24		1273.42		307.35		248.8	
HQIC	1241.19		1242.62		276.55		217.97	

Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table A.6. Threshold regression estimates for core cities of 150 to 250 thousand inhabitants.

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	18.24		16.475		15.777		15.621	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	-4.42	-4.38*	7.44	31.72***			-0.13**	0.007
	(4.48)	(2.61)	(4.83)	(1.85)			(0.06)	(0.03)
Distance to core's centre	-73.05***	-8.84***	-1.03	-2.14	-1.21***	0.0025	-0.27**	-0.018
	(8.54)	(1.49)	(11.59)	(1.49)	(0.29)	(0.036)	(0.14)	(0.014)
Population density	-0.21*	0.06			0.04***	0.016***	-0.003	-0.0002
	(012)	(0.06)			(0.009)	(0.001)	(0.004)	(0.0006)
Population size (inhabitants)	0.06***	0.01***	0.006	-0.0005	-0.00007	0.0003***	-0.00004	0
	(0.004)	(0.002)	(0.004)	(0.002)	(0.00012)	(0.00004)	(0.00005)	(0.00002)
Built apartments	-0.02	-14.78	-1.61	-7.23	-0.23	0.08		
	(6.71)	(10.65)	(7.26)	(10.57)	(0.18)	(0.26)		
Variables measured at core city								
Population density	-0.36***	-0.035	-0.14	0.21***	0.0005	-0.006***	0.004***	-0.0006
	(0.11)	(0.06)	(0.12)	(0.06)	(0.003)	(0.001)	(0.0013)	(0.0006)
Population size (inhabitants)	0.004**	0.0016	-0.003	-0.0007	0.0001**	0	-0.0001***	-0.00003**
	(0.002)	(0.001)	(0.002)	(0.001)	(0.00006)	(0.00003)	(0.00002)	(0.000012)
Number of businesses[a]	3.25	0.59	-1.1	-0.14	0.14*	-0.06	-0.08***	-0.03*
	(2.84)	(1.57)	(3.07)	(1.63)	(0.077)	(0.04)	(0.03)	(0.16)
Built apartments	102.53***	29.35***	-19.34	-5.7	0.6	0.32	-0.24	-0.18**
	(13.72)	(8.51)	(15.43)	(8.69)	(0.44)	(0.21)	(0.18)	(0.08)
costant	102.87	-51.42	935.09	-370.53	-15.56	23.74**	36.19***	13.30***
	(794.76)	(465.82)	(854.17)	(481.4)	(23.18)	(11.83)	(8.95)	(4.57)
N	290		291		291		291	
BIC	3091.51		3125.84		976.81		444.06	
HQIC	3047.52		3086.2		937.18		404.43	

Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table A.7. Threshold regression estimates for core cities of 100 to 150 thousand inhabitants.

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	15.48		14.47		18.444		13.15	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	9.22**	-3.90*	7.997*	38.56***			0.03	0.09***
	(4.31)	(2.18)	(4.83)	(1.81)			(0.07)	(0.03)
Distance to core's centre	-25.63***	-8.98***	0.82	-1.57	-0.86***	0.03	-0.22*	-0.01
	(7.53)	(0.057)	(9.94)	(1.10)	(0.12)	(0.03)	(0.13)	(0.01)
Population density	-0.27	0.08*			0.01***	0.02***	0.002	-0.0014***
	(0.19)	(0.04)			(0.0013)	(0.0009)	(0.004)	(0.0005)
Population size (inhabitants)	0.054***	0.012***	0.014**	-0.0006	0.0005***	0.0002***	-0.0003***	0
	(0.005)	(0.0014)	(0.0072)	(0.002)	(0.00009)	(0.00003)	(0.0001)	(0.00002)
Built apartments	-11.48	-7.33	1.61	-20.34***	-0.16	0.44***		
	(8.52)	(4.86)	(10.12)	(6.16)	(0.196)	(0.13)		
Variables measured at core city								
Population density	0.17*	0.07*	0.09	0.12**	-0.002	-0.0016	-0.003*	0.0004
	(0.099)	(0.038)	(0.13)	(0.05)	(0.002)	(0.0011)	(0.0015)	(0.0005)
Population size (inhabitants)	-0.004	0.0019	0.001	0.001	-0.00006	-0.00009**	0.00003	0
	(0.003)	(0.0012)	(0.003)	(0.002)	(0.00006)	(0.00003)	(0.00004)	(0.00002)
Number of businesses[a]	2.53***	1.81***	1.65	3.06***	-0.08***	-0.07***	0.004	0.01**
	(0.092)	(0.42)	(1.13)	(0.52)	(0.02)	(0.01)	(0.016)	(0.005)
Built apartments	47.97***	0.095	-40.25*	-20.11*	-0.71*	0.03	1.36***	0.07
	(18.73)	(8.35)	(23.14)	(10.67)	(0.04)	(0.24)	(0.29)	(0.10)
costant	-835.48*	-187.4	-529.92	-823.73***	40.12***	26.32***	4.95	-1.59
	(431.88)	(171.6)	(533.59)	(215.02)	(8.80)	(4.59)	(6.55)	(2.17)
N	359		362		362		362	
BIC	3621.27		3825.91		1032.82		492.97	
HQIC	3574.49		3783.71		990.61		450.77	

Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table A.8. Threshold regression estimates for core cities of 70 to 100 thousand inhabitants.

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	17.18		16.475		16.48		14.325	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	-17.53***	-0.35	7.60*	36.61***			0.04	0.05***
	(3.45)	(1.36)	(4.56)	(1.11)			(0.07)	(0.021)
Distance to core's centre	-48.29***	-4.07***	3.91	2.08**	-0.54***	-0.06***	-0.16**	0.008
	(2.74)	(0.54)	(4.83)	(0.87)	(0.10)	(0.02)	(0.07)	(0.008)
Population density	-0.49*	-0.02			0.06***	0.02***	-0.02***	-0.002***
	(0.30)	(0.03)			(0.01)	(0.0006)	(0.006)	(0.0005)
Population size (inhabitants)	0.05***	0.003***	0.004	0.0017	-0.00002	0.0001***	0.0001**	0.00004***
	(0.002)	(0.0008)	(0.004)	(0.0013)	(0.0001)	(0.00003)	(0.00005)	(0.00001)
Built apartments	-2.07	-3.19	-2.82	-27.19***	0.03	0.54***		
	(4.41)	(4.04)	(7.68)	(6.57)	(0.19)	(0.16)		
Variables measured at core city								
Population density	-0.16***	-0.05***	-0.03	-0.017	0.0018**	0.0002	0.00009	-0.0004**
	(0.027)	(0.014)	(0.04)	(0.018)	(0.0009)	(0.0004)	(0.0004)	(0.0002)
Population size (inhabitants)	-0.007***	-0.0005	0.002	0.002*	-0.0001**	-0.00002	0.00001	0.00001
	(0.0014)	(0.0007)	(0.002)	(0.0011)	(0.00005)	(0.00003)	(0.00003)	(0.00001)
Number of businesses[a]	-1.63**	-0.79*	0.21	0.07	0.005	-0.001	0.04***	-0.001
	(0.67)	(0.41)	(0.88)	(0.45)	(0.02)	(0.01)	(0.01)	(004)
Built apartments	26.01***	12.47***	11.16	-7.82	-1.01***	0.17	-0.27	0.12*
	(8.74)	(4.48)	(13.65)	(6.60)	(0.34)	(0.16)	(0.17)	(0.06)
costant	1729.07***	325.87***	-219.1	-409.19	22.70***	9.14***	0.27	0.55
	(189.45)	(91.45)	(247.80)	(107.06)	(5.89)	(2.67)	(3.04)	(1.04)
N	371		399		399		399	
BIC	3288.73		3978.08		1029.55		296.14	
HQIC	3241.52		3934.71		986.18		252.78	

Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table A.9. Threshold regression estimates for core cities fewer than 70 thousand inhabitants.

	Dependent variable							
	Commuters		Population density		Economic activity (night lights)		Built apartments	
Estimated threshold (km)	11.6		16.44		14.98		10.773	
	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA	within FUA	outside FUA
Variables measured at individual commune level								
Night lights	21.23***	0.12	4.35	27.70***			0.04	0.04***
	(4.94)	(1.04)	(3.05)	(1.11)			(0.08)	(0.01)
Distance to core's centre	-18.44***	-5.40***	0.999	0.64	-0.29*	-0.02	-0.42***	-0.01
	(6.36)	(0.47)	(4.79)	(0.77)	(0.16)	(0.02)	(0.08)	(0.006)
Population density	-2.61***	-0.02			0.10***	0.02***	-0.02**	-0.0008**
	(0.68)	(0.03)			(0.01)	(0.0008)	(0.01)	(0.0004)
Population size (inhabitants)	0.07***	0.004***	0.003	0.006***	0.00008	0.0002***	-0.00002	0
	(0.005)	(0.0009)	(0.005)	(0.001)	(0.0002)	(0.00003)	(0.00006)	(0.00001)
Built apartments	-3.13	1.25	-3.95	-9.17*	0.16	0.48***		
	(6.98)	(3.54)	(8.06)	(5.49)	(0.25)	(0.15)		
Variables measured at core city								
Population density	0.04*	-0.02**	-0.007	0.05***	0.0005	-0.001***	-0.00004	0.0001
	(0.025)	(0.009)	(0.03)	(0.01)	(0.0008)	(0.0004)	(0.0004)	(0.0001)
Population size (inhabitants)	0.009***	-0.0005	-0.0006	0.0032*	-0.00002	-0.0001***	0.00003	-0.00001
	(0.003)	(0.0012)	(0.004)	(0.0018)	(0.0001)	(0.00005)	(0.00005)	(0.00002)
Number of businesses[a]	4.43***	0.84***	0.26	0.05	-0.02	-0.02	0.03**	-0.012***
	(0.97)	(0.33)	(1.10)	(0.49)	(0.03)	(0.014)	(0.014)	(0.004)
Built apartments	-70.35***	-3.09	-4.31	9.60**	0.3	-0.16	-0.02	0.006
	(12.06)	(2.61)	(10.32)	(3.97)	(0.34)	(0.11)	(0.17)	(0.04)
costant	-923.79***	180.34**	24.56	-568.71***	9.97	20.34***	3.37	3.43***
	(230.33)	(84.71)	(267.09)	(128.58)	(8.06)	(3.55)	(3.30)	(1.14)
N	541		548		548		548	
BIC	5122.05		5600.2		1707.13		480.85	
HQIC	5069.76		5552.98		1659.91		433.63	

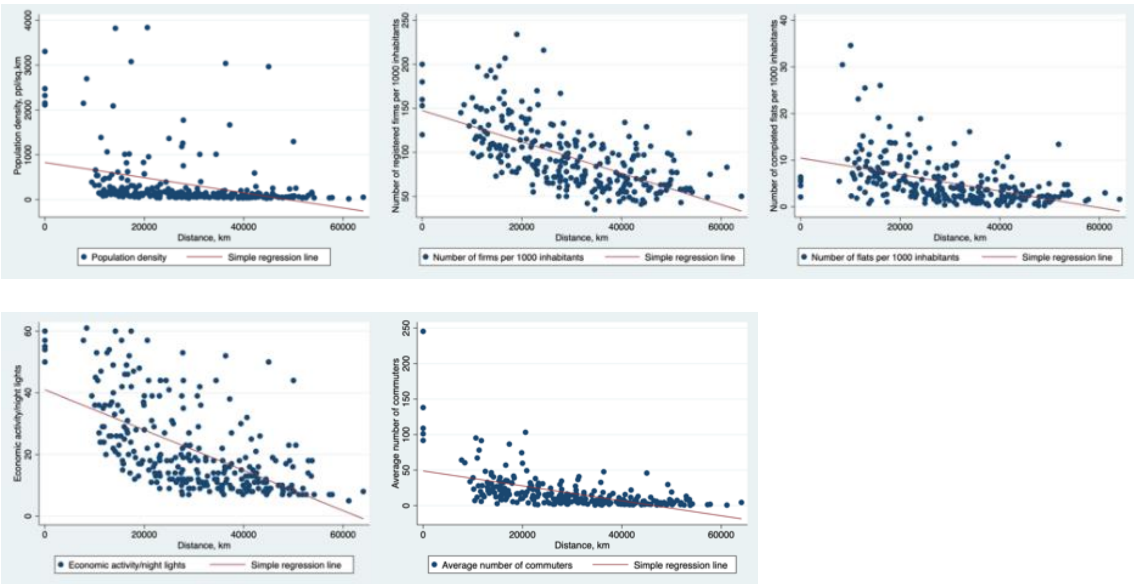
Notes: standard errors in parentheses. [a] Number of businesses registered by 1000 inhabitants. *** 1% significance level, ** 5% significance level, * 10% significance level.
Source: *own compilations.*

Table 1. The core cities grouped by population size

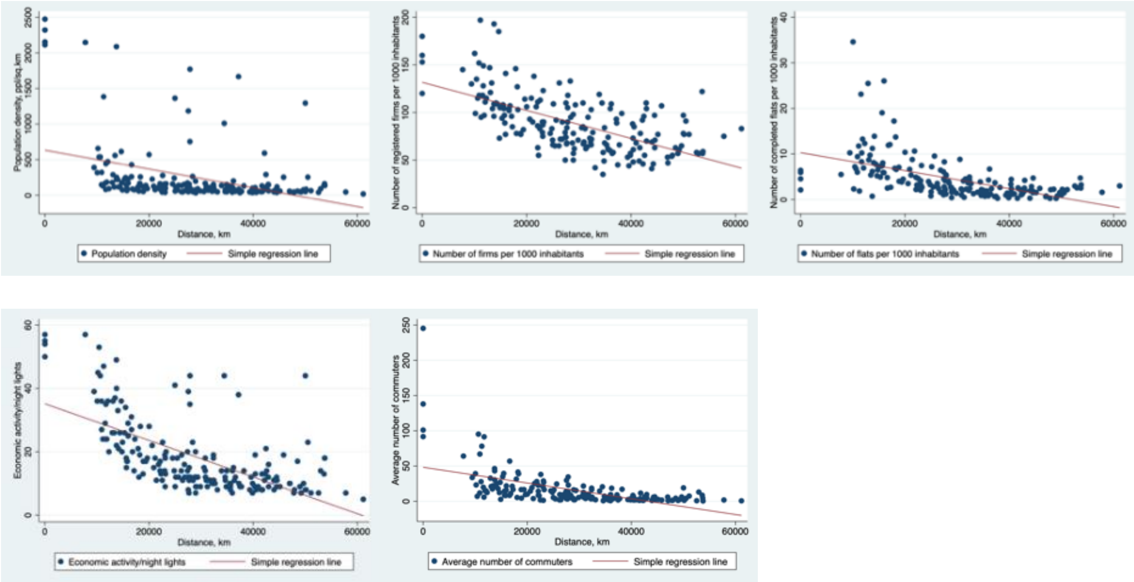
Cities by size, ths. inhabitants	Number of cities	Population	Average population	Average population dencity (ppl./km^2)	Average number of firms per 1000 inhabitants	Average number of completed flats per 1000 inhabitants	Average per capita income, zł.	Average economic activity (night lights intensity)	Total number of people commuting to work to a core city
> 500	5	4 377 482	875 496	2 474	163	4,9	4 962	55	553 104
> 500 no Warsaw	4	2 668 991	667 247	2 265	153	4,7	4 548	54	281 829
250 – 500	6	2 185 302	364 217	2 052	130	4,7	4 033	50	267 295
150 – 250	12	2 400 597	200 049	1 865	118	3,4	4 016	53	186 764
100 – 150	16	1 932 293	120 768	1 561	112	2,7	3 954	45	157 656
70 - 100	16	1 297 448	81 090	1 475	104	2,5	3 609	45	100 239
< 70	23	1 439 620	62 592	1 789	97	2,5	3 388	47	86 675
Total	78	13 632 742	174 779	1 754	112	3,0	3 797	48	1 633 562
Poland overall	2 478[a]	38 472 364	15 570[b]	224	73	2,7	3 101	15	12 48 589

Notes: [a] Number of all communes in Poland, irrespective of the urban or rural status. [b] average value across all communes in Poland. Based on the 2011 national census data (Statistics Poland, 2021).
Source: *Statistics Poland (2021) and NOAA National Geophysical Data Center (2017).*

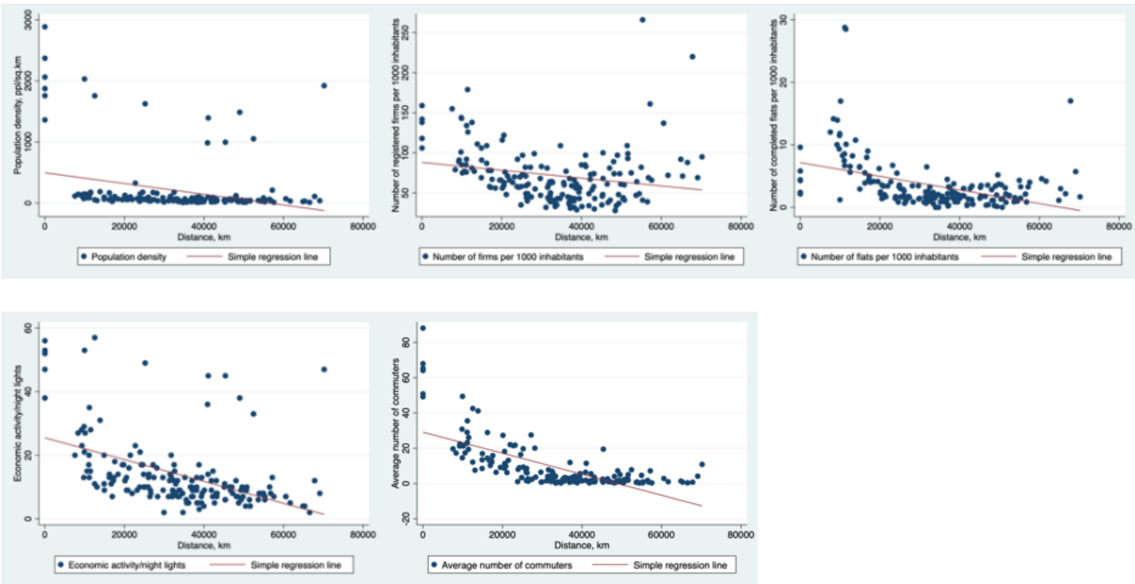
A. Core cities with population above 500 thousand inhabitants (including Warsaw).



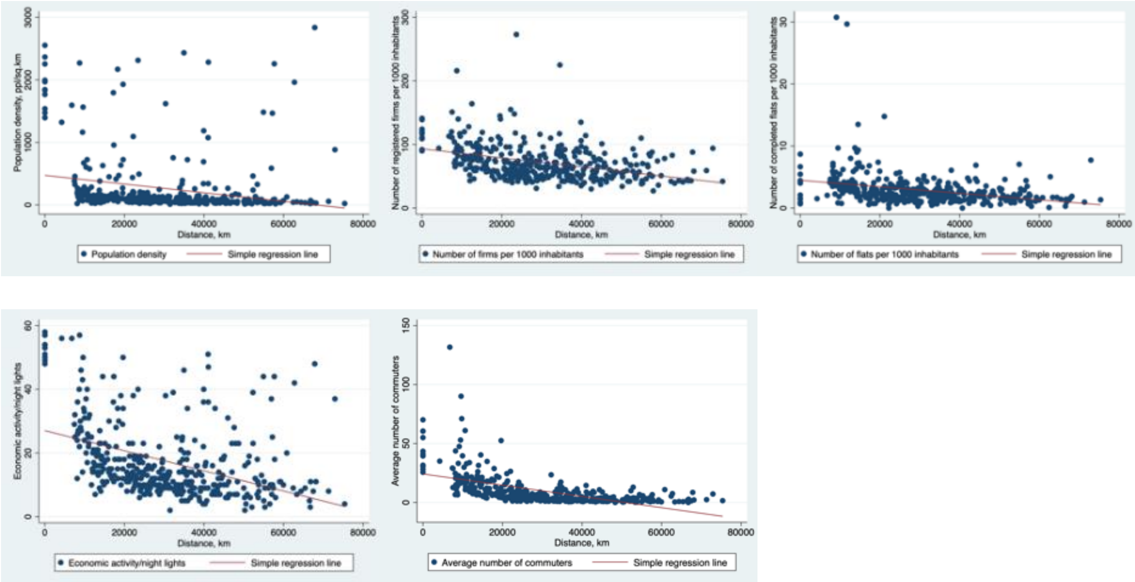
B. Core cities with population 500 thousand inhabitants without Warsaw.



C. Core cities with population 250-500 thousand inhabitants.

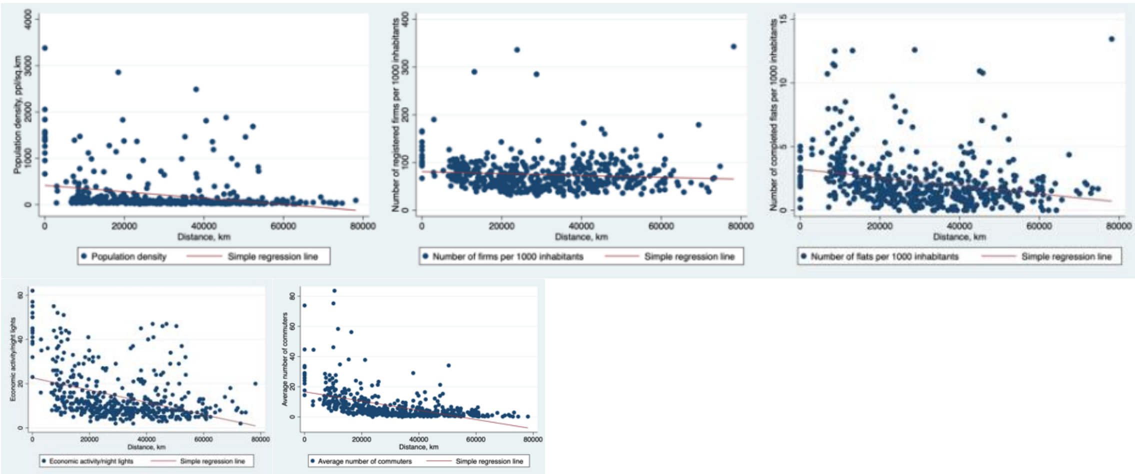


D. Core cities with population 150-250 thousand inhabitants.

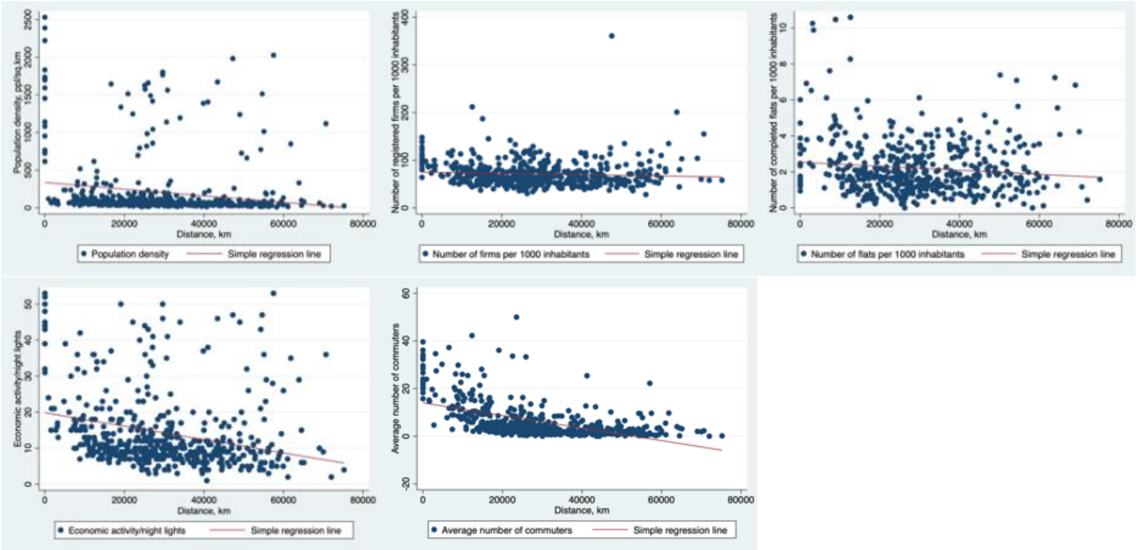


Graph 2. Commune-level variables vs. distance from the closest core city.
Notes: The Graph displays the average number of commuters from communes to core cities.
Source: *Statistics Poland (2021) and NOAA National Geophysical Data Center (2017).*

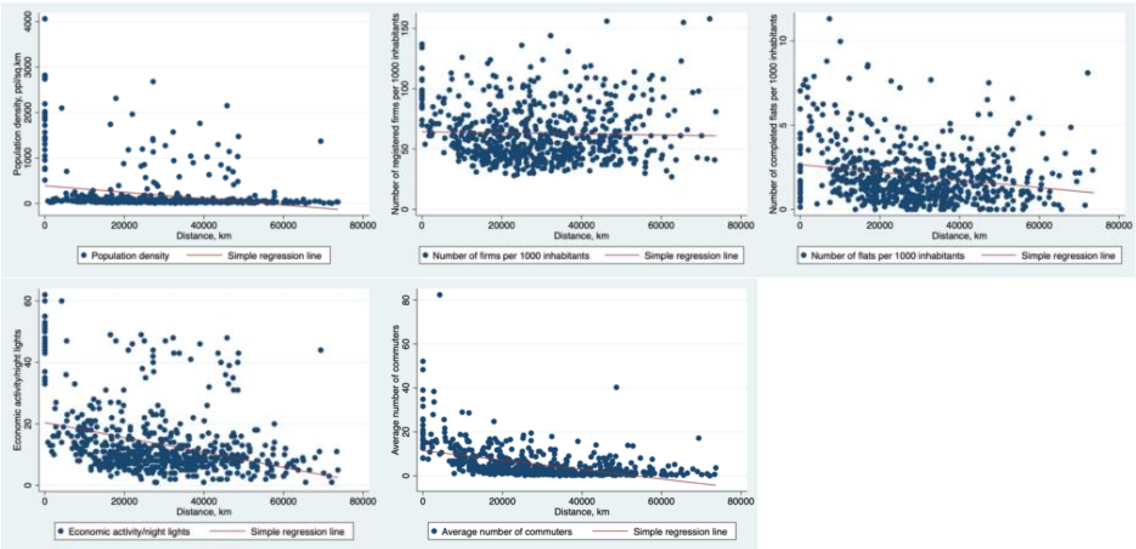
E. Core cities with population 100-150 thousand inhabitants.



F. Core cities with population 70-100 thousand inhabitants.



G. Core cities with population less than 70 thousand inhabitants.



Graph 2 cont'd. Commune-level variables vs. distance from the closest core city.
Notes: The Graph displays the average number of commuters from communes to core cities.
Source: *Statistics Poland (2021) and NOAA National Geophysical Data Center (2017).*