Original Article

Economy and Space

EPA: Economy and Space
1–21

DOI: 10.1177/0308518X231191943
journals.sagepub.com/home/epn
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Can polycentric urban development simultaneously achieve both economic growth and regional equity? A multi-scale analysis of German regions

Wenzheng Li
Department of City and Regional Planning, Cornell University, Ithaca, NY, USA

Stephan Schmidt
Department of City and Regional Planning, Cornell University, Ithaca, NY, USA

Stefan Siedentop
TU Dortmund University, Dortmund, Germany

Abstract
Polycentric urban regions have been advocated for, and justified as enhancing both economic growth and overall competitiveness while also creating more equitable and balanced metropolitan regions. We examine the role of regional polycentricity in effectuating certain desirable outcomes, specifically enhancing economic productivity and minimizing spatial disparities simultaneously in German urban regions (*Großstadtregionen*) as a case study. Using econometric analysis of both functional and morphological polycentricity measures, our results indicate that polycentric development can effectively reduce regional disparities in urban regions, but not simultaneously promote economic productivity. These findings confirm previous studies that progress toward one goal hampers progress toward another. Further investigation at a finer scale suggests that the borrowed size effect is essentially a "win-loss" game between peripheries and urban core(s) within the same urban region. Peripheries benefit from the spillovers generated by nearby urban core(s), thereby narrowing regional economic gaps and leading to more equitable regions. However, the gains of the peripheries are canceled out by the losses of the urban cores, and polycentric development has an insignificant overall effect on regional economic productivity.

Keywords
Polycentricity, urban spatial structure, economic productivity, regional disparities, Germany

Corresponding author:
Wenzheng Li, Department of City and Regional Planning, Cornell University, 129 Sibley Dome, Ithaca, NY 14853, USA.
Email: wl563@cornell.edu

Introduction

Scholarly debates on polycentric urban regions have moved beyond methodological discussions of operationalization and measurement to explaining urban spatial structure and discussing the outcomes of spatial patterns. The concept of a polycentric urban region, initially articulated to explain contemporary urban spatial structure, has been infused with a more normative agenda, serving as an organizing framework for policy intervention and planning paradigms to pursue more efficient, sustainable, and cohesive regional development (Boussauw et al., 2018; Davoudi, 2003; Faludi, 2005; Kloosterman and Musterd, 2001; Veneri and Burgalassi, 2012). This is particularly true in European regions, where the spatial policy of the EU and member states has regarded polycentric development as an integral policy tool to promote both economic competitiveness and social cohesion (BMVBS, 2006; ESDP, 1999; EU Ministers, 2020).

Despite the lofty ambitions to and realize more sustainable development, existing studies have tended to focus on evaluating a single policy objective (see, e.g. Meijers and Burger, 2010; Ouwehand et al., 2022; Sun et al., 2019; Volgmann and Münter, 2022; Wang et al., 2019). Few studies have integrated the varied goals of polycentrism to provide more comprehensive multi-objective evaluations. In fact, it remains unclear whether simultaneously creating economic efficiencies and overcoming regional inequalities is achievable (Faludi, 2005; Veneri and Burgalassi, 2012). These two goals are often interpreted as incompatible in economic literature; promoting economic competitiveness may often result in an exacerbation of regional equity (Davoudi, 2003). Policymakers could be misled by the empirical evidence of single-objective evaluations and ignore the possible adverse effects on others.

The primary focus of this study is to examine whether or not polycentric development can result in greater economic growth *and* fewer regional inequalities in German urban regions (*Großstadtregionen*), utilizing cross-sectional regressions for 2007 and 2017. Our result suggests that while polycentricity may effectively reduce regional disparities, it may not necessarily lead to higher economic productivity. To explore potential reasons for this finding, we conduct an additional district-scale analysis, examining whether peripheral locations within polycentric urban regions are more likely to borrow size from the nearby urban core(s), enhancing economic performance, compared with their monocentric counterparts. Methodologically, this study, as far as we know, represents the first quantitative attempt to examine the "win-win" hypothesis of polycentricity in Germany using reliable econometric models. We pursue causal inference using the two-stage least square regression (2SLS) and carefully review the robustness of estimates using functional and morphological measures of polycentricity and three measures of regional disparities.

The paper is structured as follows. Section "Literature review" discusses the theoretical underpinnings of polycentricity in achieving the benefits of economic efficiencies and regional equalities. Section "Methods and data" describes the data and methods, emphasizing the empirical strategies that validate the causal inference between polycentricity and social and economic goals. Section "Results and findings" interprets the results of two types of regressions, one at the urban region scale and another at the district scale. The last section discusses the findings and policy implications.

Literature review

Polycentricity and economic productivity

Essential to the debate of monocentric versus polycentric models are two countervailing forces—agglomeration economies and agglomeration diseconomies. Agglomeration economies, defined as the cost-saving due to the colocation of economic activities, have been viewed as crucial in driving urban productivity and urban spatial structure (Fujita and Thisse, 2002; Rosenthal and Strange, 2020). However, the relationship between city size and economic productivity usually represents an inverted

U-shape curve, suggesting that, as cities exceed their optimal sizes, agglomeration diseconomies occur such that firms' production suffer from decreasing returns as congestion and factor prices increase (Capello and Camagni, 2000; Lee, 2007). Firms and households then relocate to peripheral regions, forming suburban subcenters and edge cities that ultimately establish polycentric urban regions. Research has suggested that a polycentric configuration is preferred over a monocentric one with equivalent size, as it enables greater capacity to keep agglomeration costs under control and continues to reap benefits from agglomeration economies (Hall and Pain, 2006; Meijers and Burger, 2010).

More recently, a growing literature, inspired by the success of the globally recognized polycentric regions, such as the Randstad in the Netherlands, the Yangtze River Delta of China, and the Rhine-Main (Frankfurt) region in Germany, suggests that global economic competitiveness is enhanced through larger urban agglomerations in which distinct cities form integrated functional regions characterized by an extensive geographical area, polycentric urban structure, and active involvement in the global economy (Hall and Pain, 2006; Parr, 2008). These empirical realities suggest that the advantages of agglomeration, traditionally constrained to local economic activities, are able to be scaled up to regions (Meijers et al., 2018; Parr, 2002; Phelps, 2004).

Several new theoretical concepts have been suggested to explain the spatial diffusion of agglomeration benefits as urban spatial patterns have become more decentralized and polycentric. For instance, Parr (2004) proposed the notion of "*regional externalities*" to describe the externalities generated by the spatial diffusion of economic activities at regional scales. Similarly, "*urban network externalities*" proposed by Capello (2000) suggests that functional networks between proximate cities could spatially extend the benefits of agglomeration through regional synergies and complementarities. Polycentric urban regions, characterized by less pronounced hierarchical differentiation and multidirectional linkages, have been regarded as a more economically efficient urban configuration at the regional scale, as they are better suited to realize the network/regional externalities than monocentric regions.

However, the empirical literature assessing the economic benefits of polycentric urban regions has drawn mixed conclusions. Meijers and Burger (2010) found polycentric regions have higher labor productivity than monocentric ones in the US, with small regions benefiting more from polycentricity than large regions. Veneri and Burgalassi (2012) drew a similar conclusion by investigating the economic productivity of Italian NUTS-2 regions. In contrast, Brezzi and Veneri (2015), in a study of OECD functional regions, concluded that monocentric structures promote economic productivity. This finding has been recently corroborated by Ouwehand et al. (2022) in a pan-European study that utilized NUTS-2 regions. Empirical studies in China have consistently shown a negative relationship between polycentricity and economic/labor productivity (Li et al., 2019; Li and Liu, 2018; Wang et al., 2019), suggesting that monocentric development is more favorable for boosting economic growth in China.

Polycentricity and regional inequalities

The potential of polycentricity to promote regional equality has been mentioned in various EU spatial policy documents, including the CEC (2004), ESDP (1999), and in European Union (2011). Among them, polycentrism is regarded as a more efficient urban configuration to realize regional networks and cooperation so that the economic growth of large cities would trickle down to medium- and small-sized cities and ultimately to peripheral and lagging areas. In other words, the polycentric configuration would lessen regional economic gaps because multiple cities could benefit from regional economic growth rather than merely the urban core (Meijers and Sandberg, 2008; Rauhut and Humer, 2020).

The theoretical basis for the use of polycentrism in achieving regional economic convergence is closely related to Krugman's (1991) core-periphery model, which employs two opposing forces, agglomeration and dispersion, to explain spatial inequalities (Fujita and Thisse, 2002). The agglomeration force generates divergent growth of regional wealth, as firms and jobs cluster in the urban core with higher local demand, thereby driving wages up. Conversely, the dispersion force promotes regional convergence, as firms and jobs relocate to peripheries due to intense competition and high factor costs in the urban core (Tabuchi and Thisse, 2002). The level of inequality is contingent upon which forces dominate.

The effect of polycentrism on regional equality has been studied in several countries with mixed results. Meijers and Sandberg (2008) conducted one of the earliest studies for EU countries and found no significant relationship between the two. However, a recent update by the authors using panel model and more robust polycentricity measures found that polycentricity could indeed reduce regional disparities (Meijers and Sandberg, 2021). Malý (2016) examined functional regions in the Czech Republic and suggested that the relationship depends on the indicators to measure regional disparities. Veneri and Burgalassi (2012) found that polycentricity is associated with larger regional gaps in their investigation of Italian NUTS-2 regions. Recent studies by Sun et al. (2019) observed that regional wealth distributes more evenly in monocentric prefectural regions in China because they can share the benefits of agglomeration through labor mobility, whereas polycentric regions did not "borrow functions or performance" from one another.

"Borrowed size": *Linking regional inequalities and economic productivity*

Although the assumed simultaneous outcomes of polycentricity have yet to find a sound theoretical underpinning and universal supports from empirical studies, one concept that could shed light on connection between regional inequalities and economic productivity is the notion of "borrowed size," first introduced by Alonso (1964) and more recently reinterpreted as a positive outcome of network externalities (Meijers et al., 2016; Meijers and Burger, 2017). Borrowed size suggests that smaller cities can achieve better economic performance by leveraging network spillovers from nearby large cities. The antithesis of this concept is known as "*agglomeration shadows*," which refers to the situation where the development of small cities is inhibited by the competition of nearby large cities.

The definition of polycentric urban regions (PURs) highlights the importance of balanced and multidirectional connections among member cities, which generate mutual spillovers and facilitate borrowing of size from adjacent cities. Peripheral cities in monocentric regions, in contrast, are expected to be more associated with the agglomeration shadows due to the dominant urban core. That said, in the presence of borrowed size, spillovers from large cities could stimulate the growth of nearby small cities, narrowing the economic gap between urban cores and peripheries and ultimately leading to greater regional equality. The prosperity of the regional economy in PURs hinges on whether the growth of peripheries comes at the expense of large urban cores or if both cores and peripheries borrow size via mutual spillovers. Conversely, if the agglomeration shadows prevail, regional core(s) would compete with peripheral subcenters for resources, resulting in higher regional gaps and exacerbating regional disparities. The overall economic performance of the monocentric urban region primarily relies on traditional agglomeration economies and the economic productivity of the urban core.

To this end, we anticipate that the simultaneous outcomes for large metropolitan regions (in this contribution the German *Großstadtregionen*) would be largely attributed to the interplay between the effects of "borrowed size" and "agglomeration shadows" of subregional districts. If the hypothesis holds that PURs are more conducive to small and peripheral districts for "borrowing size," PURs would be economically more equitable than monocentric urban regions (MURs); otherwise, PURs would not demonstrate the advantages over MURs in mitigating regional disparities. Scenarios in which PURs promote economic productivity are somewhat more nuanced. This is because MURs subject to agglomeration shadows may also demonstrate good overall economic performance, as urban cores may develop at the expense of peripheries. As such, we expect that if both urban cores and peripheries could borrow size from each other, PURs would perform better than MURs, whereas the winner is uncertain if only peripheries could borrow size or if they are better off at the expense of urban cores.

Methods and data

Study regions

We choose German urban regions (*Großstadtregionen*) as the appropriate regional delineation to investigate the simultaneous outcomes of polycentricity. *Großstadtregionen* are defined by the Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR) as a region consisting of one or multiple urban cores with a population greater than 100,000 and hinterlands (peripheries) with strong commuting relationships with the core cities. They are, therefore, a good representation of the regional labor market and the functional urbanized area. However, a spatial mismatch occurs in data processing, as the urban regions are delineated and aggregated from municipalities, whereas the regression variables we collected are at the district (*Landkreis*) scale. To ensure that the variables reflect the social and economic status of the urban region they represent, we re-delineate urban regions following the borders of districts while referencing the official municipality-based urban regions. The final product of urban regions consists of 45 regions and should be considered a good approximation of the original urban regions[1] (see Figure 1).

Operationalizing polycentricity

Measuring polycentricity has stimulated extensive debates in the literature primarily due to the ambiguity around defining an urban center and measuring the degree of balance between these centers (Derudder et al., 2021; Münter and Volgmann, 2021; Thomas et al., 2022). This study uses the municipal association (*Verbandsgemeinde*) as the basic spatial unit to measure polycentricity, relying on three commonly used measures from both morphological and functional perspectives. Functional polycentricity is defined as the extent to which commuting flows between identified centers are evenly distributed, following the standard deviation method introduced by Green (2007). The method is expressed in equation (1):

$$P_F(n) = \left(1 - \sigma_f / \sigma_{fmax}\right) * \Delta \tag{1}$$

where $P_F(n)$ represents the functional polycentricity for a region incorporating n centers. σ_f is the standard deviation of the commuting flows between these centers, and σ_{fmax} is the standard deviation of the commuting flows of an absolute monocentric scenario with two nodes; one has zero commuting flows, and another has the highest commuting flows within the region. Δ is the density of the network, defined as the ratio of actual commuting flows to the maximum commuting flows that are theoretically possible within the region.

Morphological polycentricity, on the other hand, utilizes patterns of employment distribution within a region and operationalizes polycentricity using the rank-size distribution method following Meijers and Burger (2010) and the standard deviation method introduced by Liu and Wang (2016). The detailed steps of quantifying these metrics are available in the Supplemental Materials.

According to Zhang and Derudder (2019), polycentricity measures are sensitive to the number of centers incorporated. We include a fixed number of large centers sorted by total employment in each

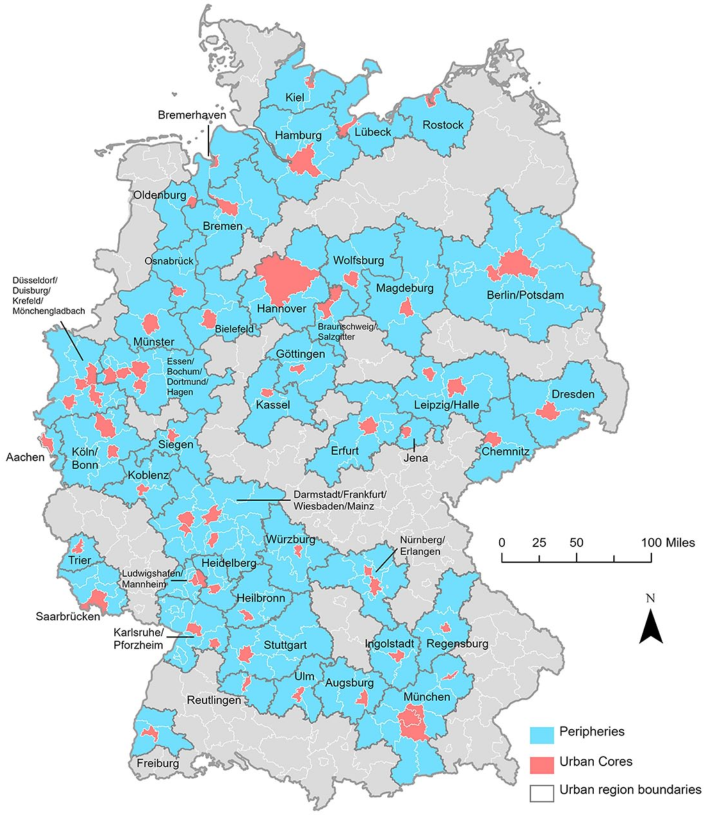

Figure 1. The re-delineated German urban regions following the borders of districts. Urban cores are marked in red, and the peripheries are in blue.

region, as polycentricity tends to be judged by the size distribution of just a handful of large cities. We consider the polycentricity values of the top two, three, and four centers (namely $P_F(2), P_F(3)$, and $P_F(4)$) of each region and average them to obtain the final polycentricity indices for the three measures, following precisely the method used by Meijers and Burger (2010), Ouwehand et al. (2022), and Wang et al. (2019). To ensure the robustness of our conclusion, we further generate polycentricity indices that incorporate the top six and eight centers for each region, and compare the results obtained with these measures against those obtained using the top four centers. Our investigation indicates that the inclusion of additional centers in operationalizing polycentricity produce only minor differences, with little impacts on the regression results, irrespective of whether morphological or functional polycentricity measures are used.

Empirical estimation strategy

Ordinary least square (OLS) model. The econometric analysis to test the simultaneous outcomes of polycentricity starts with the cross-sectional regressions for urban regions. Equation (2) presents the basic model to investigate the impact of polycentricity on regional equalities.

$$Gini_i = c_i + \alpha_0 Poly_i + \alpha_1 GDPpc_i + \alpha_2 Pop_i + \alpha_3 Unemploy_i + \alpha_4 Redistr_i + \alpha_r + \epsilon_i \tag{2}$$

where $Gini_i$ is the dependent variable defined as the Gini coefficient for urban region i. We measure regional economic inequalities using three inequality indicators: Gini coefficient (Gini), coefficient of variation (Cov), and population-weighted Gini coefficient (pwgini), following Gluschenko (2018). The steps for generating these measures are shown in Appendix 1. $Poly_i$ represents the degree of polycentricity for the urban region i, and is measured by a functional polycentricity index, Poly_Fun, and two morphological polycentricity indices, Poly_morp and Poly_Ranksize. The control variables include GDP per capita, total population to control for agglomeration, unemployment rate to control for regional economic structure, and fiscal equalization funds from states to municipalities (*Schlüsselzuweisungen*) (Redistribution per capita) as a control for policy invention. In addition, we include four regional dummies (α_r), east, north, west, and south, as controls for unobserved variations[2] in price, technology, and climate, following previous studies by Meijers and Burger (2010) and Ouwehand et al. (2022).

The model to examine the impact of polycentricity on the economic productivity of urban regions is shown in equation (3):

$$GDPpc_i = c_i + \beta_0 Poly_i + \beta_1 PhyInv\_pc_i + \beta_2 Pop_i + \beta_3 Education_i + \alpha_r + \epsilon_i \tag{3}$$

where $GDPpc_{it}$ is the proxy for economic productivity measured as GDP per capita for urban region i. We include a number of widely accepted control variables, including per capita physical investment expenditure (*Ausgaben für Sachinvestitionen*) (investment per capita) as a proxy of public capital input, the share of employees with a college degree as a measure of human capital (Education), and total population (Population) as a measure of urbanization economies, following the studies of Li and Liu (2018) and Meijers and Burger (2010). Expenditure on physical investment captures the public investment in real estate, infrastructure, and construction, which is considered important capital input of local economic growth. The positive effects of human capital and agglomeration on economic growth have been well-documented in previous studies (Baldwin and Martin, 2004). Similar to the model of regional disparities, we include four regional dummies to control for unobserved effects caused by price, technology, and climate differences.

The third model at the district scale is designed to investigate whether districts embedded in polycentric urban regions are able to borrow size from each other, thereby enhancing economic performance, compared to their monocentric counterparts. Specifically, we aim to examine whether such benefits are shared by both urban cores and peripheries, resulting in a "win-win" scenario, or whether they favor one at the expense of the other, leading to a "win-loss" scenario. The basic model is quite similar to the model of urban regions as equation (3) but at the district scale. The model extension, as expressed below, includes an interaction term to assess the heterogenous effect of polycentricity on urban cores and peripheries.

$$GDPpc_d = c_d + \gamma_0 Poly_d \times UrbanCore_d + \gamma_1 Poly_d + \gamma_2 UrbanCore_d + \gamma \boldsymbol{x}_d + s_d + \epsilon_d \tag{4}$$

where $UrbanCore_d$ is a dummy variable denoting whether a district d is an urban core (equal one) or a periphery within an urban region. $Poly_d$ represents the polycentricity degree of the urban region in which the district d is embedded. Whether peripherals or urban cores (or both) can borrow size, depend on the significance and signs of γ_0 and γ_1. $\boldsymbol{x}_d$ stands for a vector of district-level controls that are identical to those used in equation (3), and s_d is the state fixed effects to control for unobserved variance at district scale.

Two-stage least squares (2SLS) regressions. A broad range of studies have documented the endogeneity issue arising from possible reverse causation; that is, polycentricity can be regarded as both a cause and consequence of regional socio-economic realities (Meijers and Burger, 2010; Wang et al., 2019).

We employ the 2SLS estimates and instrumental variables to correct the estimation bias resulting from the endogeneity issue in the OLS model. The two instrumental variables (IVs) we generated are the historical degree of polycentricity for urban regions in 1871, measured based on the municipality population collected in the 1871 census, and the natural topography, defined as the second derivative of elevation. Using historical urban spatial structure and natural conditions as IVs follows the classic works by Baum-Snow (2020) and Ciccone and Hall (1993). The instrumental variables should meet the exclusion restriction requirement to resolve the endogeneity issue. That is, the instruments would affect the current economic realities (the dependent variable) only through their impacts on the current urban spatial structure. We believe the exclusion restriction is met in our case because Germany has experienced dramatic changes during the past 150 years, including economic collapses and rebuilding as well as massive population migrations due to the World Wars. It is thus highly unlikely that the degree of polycentricity in 1871 is related to the current economic conditions. In addition, it is well-documented that topographic factors, such as elevation, slope, and soil types, could significantly influence land uses and urban spatial structure while exerting no direct effects on current economic conditions (Wang et al., 2019).

Datasets

The datasets for the econometric analysis come from the INKAR data platform of the Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR). The commuting flow data used to generate the polycentricity indices are collected from the Federal Employment Agency of Germany and is only available for 2007 and 2017. As for the instrumental variables, we access the historical local population database provided by Roesel (2022)[3] to generate the historical polycentricity index, and the DEM for computing the terrain curvature from the SRTM DEM product released by NASA. See Table 1 for the descriptive statistics and data sources.

Results and findings

The spatial patterns of the degree of polycentricity for urban regions

Our analysis begins with mapping the degree of polycentricity for urban regions using one functional polycentricity index (Poly_Fun) and two morphological polycentricity indices (Poly_Morp, Poly_Ranksize), as illustrated in Figure 2a to c. We readily observe that the spatial patterns of polycentricity for the three measures are quite similar, depicting a trend of increasing polycentricity from northeast to southwest. Moreover, the top five most polycentric and monocentric regions largely overlap across different measures. The most monocentric regions measured by functional polycentricity include Berlin, Hamburg, Bremen, München, and Dresden, widely recognized as some of the most populous, monocentric, and economically vital regions in Germany. The two morphological measures replace Dresden with Rostock on their list while retaining the other four regions. The most polycentric regions identified by the functional measure are the well-known polycentric region of Essen-Bochum-Dortmund-Hagen located in the broader Rhine-Ruhr area, the Ludwigshafen-Mannheim located in the broader Rhine-Neckar area, and the three smaller regions in the southwest, Reutlingen, Heilbronn, and Saarbrücken. The morphological measures yield an almost identical list, with the only exception being the Düsseldorf-Duisburg-Krefeld polycentric region within the broader Rhine-Ruhr area, which does not appear based on the functional measure.

Furthermore, we examine the relationship between the three measures of polycentricity to determine whether the degree of polycentricity according to different methods differs significantly from each other. As depicted in Figure 2d, the three measures present a perfect linear relationship, with 73% of the variation in functional polycentricity (Poly_Fun) explained by Poly_Morp, and 72%

Table 1. Descriptive statistics of variables.

	Year	*N*	Mean	Std. Dev.	Median	Min	Max	Data sources
Variables at the Urban Region level (in logarithmic form)								
Functional polycentricity	2007	45	−1.151	0.506	−1.214	−2.390	−0.079	The Federal Employment Agency of Germany[a]
	2017	45	−1.142	0.539	−1.230	−2.496	−0.114	
Gini	2007	44	−1.874	0.392	−1.889	−2.827	−0.891	The INKAR data platform of the Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR)[b]
	2017	44	−1.989	0.449	−2.003	−2.925	−0.796	
GDP per capita	2007	45	3.381	0.197	3.374	3.060	3.909	
	2017	45	3.647	0.201	3.621	3.323	4.143	
Population	2007	45	13.827	0.791	13.650	12.408	15.441	
	2017	45	13.835	0.798	13.632	12.462	15.489	
Unemployment	2007	45	1.826	0.406	1.84	0.989	2.520	
	2017	45	1.456	0.351	1.522	0.602	1.993	
Redistribution per capita	2007	45	5.632	0.425	5.639	4.246	6.401	
	2017	45	6.006	0.416	6.115	4.462	6.617	
Investment per capita	2007	42	5.445	0.435	5.615	4.480	6.183	
	2017	45	5.590	0.438	5.594	4.425	6.440	
Education	2017	45	2.695	0.249	2.679	2.170	3.282	
Variables at the Districts level (in logarithmic form)								
Functional polycentricity	2007	230	−1.139	0.562	−0.991	−2.390	−0.079	Same as above
	2017	250	−1.126	0.583	−1.019	−2.497	−0.114	
GDP per capita	2007	230	3.322	0.375	3.250	2.708	4.534	
	2017	250	3.563	0.346	3.508	2.975	5.149	
Investment per capita	2007	230	5.568	0.499	5.630	3.934	6.710	
	2017	250	5.587	0.539	5.573	3.578	6.758	
Population	2007	230	12.181	0.586	12.156	10.455	14.087	
	2017	250	12.134	0.611	12.100	10.44	14.191	
Education	2017	250	2.500	0.371	2.425	1.768	3.501	
UrbanCore	—	230	0.231	0.423	0	0	1	

[a]https://www.arbeitsagentur.de/en/welcome.
[b]https://www.inkar.de/

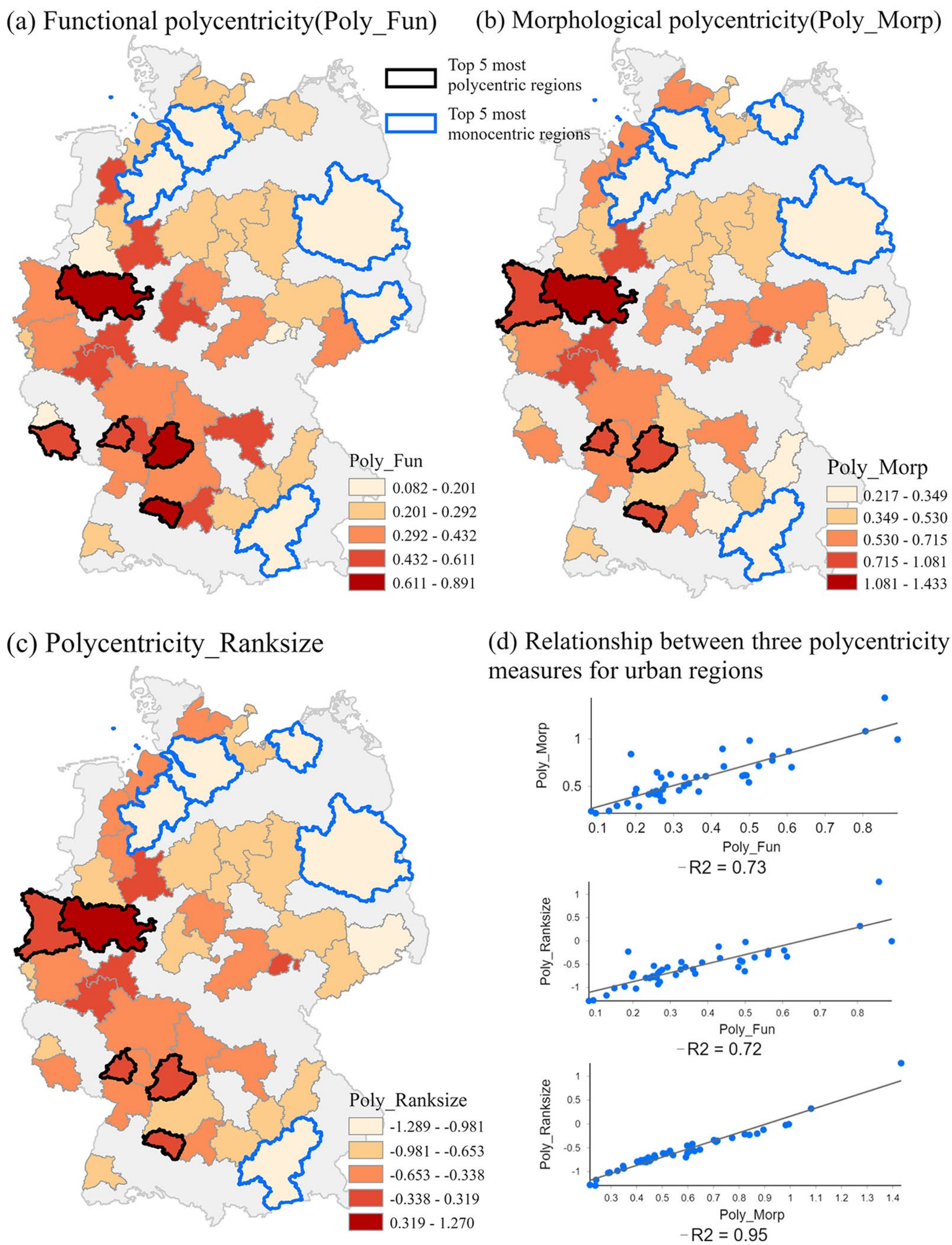

Figure 2. (a–c) The spatial patterns of the degree of polycentricity measured by functional polycentricity (Poly_Fun) and morphological polycentricity (Poly_morp and Poly_Ranksize) and (d) the relationships between three polycentricity measures, as shown by scatterplots and fitted lines.

Table 2. Cross-sectional regressions to test the effect of functional polycentricity (Poly_Fun) on regional disparities, as measured by the Gini coefficient in 2007 and 2017 using OLS and 2SLS estimators.

Variables[c] (in logarithmic form)	OLS		2SLS	
	2007	2017	2007	2017
	Model (1)	Model (2)	Model (3)	Model (4)
Poly_Fun	−0.359* (0.1426)	−0.4787** (0.1471)	−0.3145 (0.1633)	−0.5552** (0.163)
Population	−0.2594** (0.0727)	−0.1627** (0.0583)	−0.2519** (0.0631)	−0.1733** (0.0544)
GDP per capita	1.9814** (0.4302)	2.0449** (0.2464)	1.9379** (0.3669)	2.0841** (0.2345)
Unemployment	0.6553* (0.322)	0.2798 (0.3382)	0.5987* (0.2934)	0.3336 (0.3258)
Redistribution per capita	−0.0418 (0.1823)	0.2467 (0.149)	−0.0848 (0.1531)	0.2989* (0.1425)
Kleibergen-Paap *F*-statistics (Weak IV test)			16.366	14.032
Sargan-Hansen statistics (overidentification test)			0.919	0.480
Endogeneity test			0.584	0.470
Regional dummies[a]	Yes	Yes	Yes	Yes
Constant	−6.5294** (2.2097)	−9.802** (1.8894)	−6.0319** (1.883)	−10.323** (1.8695)
Observations[b]	44	44	44	44
R^2	0.5964	0.6773	0.5935	0.6741

Robust standard errors are in parentheses.
[a]All regressions include regional dummy variables (East, North, West, South).
[b]The urban region Aachen is removed from all models due to missing values of the Gini coefficient.
[c]All variables, except the dummy variables, are in logarithmic form.
$^{**}p < 0.01$. $^{*}p < 0.05$.

explained by Poly_Ranksize. The two morphological measures show an even higher correlation, with 95% of the variation in one measure explained by the other. Our analysis indicates that, for German urban regions, functional and morphological polycentricity do not produce significant variation.

Regression analysis for urban regions

Table 2 presents the OLS and 2SLS estimates of the impact of functional polycentricity on regional inequalities measured by the Gini coefficient, which controls for economic, policy, and demographic differences as well as regional variations. We report robust standard errors to address heteroskedasticity and a series of tests to validate the instrumental variables and the consistent 2SLS estimates. The Kleibergen-Paap *F*-statistics of 2SLS regressions (Models 3 and 4) indicate that our IVs are highly relevant to the endogenous variable, and thus are not weak. We use the over-identification test to assess the exogeneity of the IVs, as we include two IVs for one endogenous variable. The insignificant Sargan-Hansen statistics suggest that our IVs are exogenous. Moreover, the endogeneity test assesses whether our assumed endogenous variable, the functional polycentricity, is truly endogenous in the OLS model. The insignificant results indicate it is exogenous; thus, the OLS estimates are reliable and more efficient than the 2SLS estimates. Nonetheless, we report both OLS and 2SLS results for robustness.

The significant and negative OLS estimates in models 1 and 2 suggest that functional polycentricity (Poly_Fun) can effectively reduce regional inequalities in both researched years (2007 and 2017). In other words, polycentric development leads to a more equalized distribution of regional wealth than a monocentric pattern. A doubling of the degree of polycentricity (a 100% increase) reduced regional inequalities by 35.9% and 47.8% in 2007 and 2017, respectively. The 2SLS regressions (models 3 and 4) show similar estimates of a 31.4% and 55.5% reduction in regional disparities, even though the coefficient of polycentricity in model 3 is insignificant at a 5% significance level ($t = 1.92$).

To further examine the robustness of the effects of different polycentricity measures on regional disparities, we report in Table 3, panel A, the 2SLS estimates of the three polycentricity measures using various regional disparity measures as dependent variables. Our results demonstrate that, among the three measures, the coefficients of polycentricity are significant in all models of 2017, regardless of the polycentricity and regional disparities measures used. Most of the models in 2007 exhibit significant coefficients with expected signs, including all models employing population-weighted Gini coefficient (pwgini) as the measure of regional disparities and two out of three models using the coefficient of variation (Cov). However, all models employing the Gini coefficient as the measure of regional disparities are statistically insignificant at a 5% level, suggesting that the effects of polycentricity may differ depending on the measures of regional disparities. Nevertheless, since the majority of models yield consistent results in multiple robustness check, we can generally conclude that both functional and morphological polycentric development could effectively reduce regional disparities in German urban regions. This further implies that small cities in polycentric regions could benefit from the spillovers generated by the nearby large cities, thereby narrowing the economic gaps between the affluent urban cores and peripheries. We will provide further evidence for this claim in section "Regression analysis for districts" using district-level regressions.

Table 4 presents the effect of functional polycentricity on economic productivity measured as GDP per capita while controlling for physical investment, human capital, and population, as well as regional variations caused by climate, price, and technology. We report robust standard errors and use a set of tests to validate the use of IVs. Our control variables reveal that a larger population (in 2007), a higher proportion of educated workers, and increased physical investment are positively associated with economic growth. In particular, a doubling of a region's population in 2007 contributed to a 6.5% (OLS) and 7.2% (2SLS) increase in GDP per capita, suggesting the positive effect of urbanization economies. This result is comparable to estimates from studies on US metropolitan areas (7%–10%) by Meijers and Burger (2010) and slightly lower than those from a pan-European study (15%–18%) by Ouwehand et al. (2022). However, in the 2017 regressions, we do not observe a significant effect of population on economic productivity. A closer examination of the data reveals that two small regions, Wolfsburg and Ingolstadt, with relatively high GDP per capita, have heavily influenced the regression results. Both regions are home to large automobile manufacturers, and their prosperity suggests that localization economies within the automobile industries have profoundly influenced certain German regions.

Concerning our variables of interest, the insignificant coefficients of functional polycentricity for both the OLS and 2SLS models suggest that a polycentric region may not produce greater economic productivity compared with a monocentric region. Morphological polycentricity measures results in similar outcomes, as shown in Table 3 panel B. The insignificant results raise doubts about the existence of the borrowed size effect and suggests two possible explanations regarding the mutual spillovers of cities within polycentric regions. The first involves the rejection of the borrowed size hypothesis and the notion of regional external scale economies, concluding that no mutual spillovers exist between cities within polycentric regions. The second assumes that small cities may benefit from spillovers of nearby large cities, while their growth is achieved at the expense of the large ones, thereby neutralizing the effect of borrowed size. We will further demonstrate the validity of the second scenario in the following section.

Regression analysis for districts

Table 5 illustrates the impact of functional polycentricity on economic productivity at the district scale. The purpose here is to investigate whether cities/districts situated within polycentric urban regions have a greater capacity to borrow size, thereby enhancing performance; if so, whether the benefits accrue to both urban cores and peripheries or whether one gains at the expense of the other.

Table 3. Robustness check of the effects of different measures of polycentricity on regional disparities and economic productivity using 2SLS estimators.

Panel A: Robustness check for regional disparity regressions

Variables	2007-2SLS			2017-2SLS		
	Gini coefficient (Gini)	Coefficient of variations (Cov)	Population-weighted Gini (pwgini)	Gini coefficient (Gini)	Coefficient of variations (Cov)	Population-weighted Gini (pwgini)
Poly_Fun	−0.3145 (0.1633)	−0.3732* (0.1718)	−0.4768** (0.1794)	−0.5552** (0.163)	−0.5558** (0.1628)	−0.6690** (0.1685)
Poly_Morp	−0.2855 (0.1703)	−0.3475* (0.1701)	−0.4675* (0.1938)	−0.5857** (0.1919)	−0.5903** (0.1988)	−0.7043** (0.2060)
Poly_Ranksize	−0.5158 (0.3213)	−0.6084 (0.3254)	−0.8489* (0.3726)	−1.0157** (0.3493)	−1.032** (0.3611)	−1.2186** (0.3765)

Panel B: Robustness check for economic productivity regressions

Variables	2007-2SLS	2017-2SLS
	GDP per capita	GDP per capita
Poly_Fun	0.0347 (0.0805)	0.0847 (0.0868)
Poly_Morp	0.0359 (0.0685)	0.967 (0.0988)
Poly_Ranksize	0.0625 (0.1708)	0.1580 (0.1836)

Robust standard errors are in parentheses. Regressions include all control variables.
$^{**}p < 0.01$. $^{*}p < 0.05$.

Table 4. Cross-sectional regressions to test the effect of functional polycentricity (Poly_Fun) on economic productivity measured by GDP per capita in 2007 and 2017 using OLS and 2SLS estimators.

Variables (in logarithmic form)	OLS		2SLS	
	2007	2017	2007	2017
	Model (1)	Model (2)	Model (3)	Model (4)
Poly_Fun	−0.0435 (0.0537)	−0.0201 (0.058)	0.0347 (0.0805)	0.0847 (0.0868)
Population	0.0723* (0.0351)	0.0427 (0.0311)	0.0656* (0.0288)	0.0407 (0.0301)
Investment per capita[b]	0.1459* (0.0539)	0.2148* (0.0966)	0.1263** (0.0477)	0.205* (0.0899)
Education	0.2722* (0.1222)	0.3432* (0.1272)	0.3363* (0.1399)	0.4407** (0.1565)
Kleibergen-Paap *F*-statistics (Weak IV test)			30.293	36.150
Sargan-Hansen statistics (overidentification test)			0.741	2.043
Endogeneity test			2.305	3.187
Regional dummies[a]	Yes	Yes	Yes	Yes
Constant	0.5563 (0.4443)	0.7583 (0.5914)	0.6981 (0.4767)	0.7263 (0.5733)
Observations[c]	42	45	42	45
R^2	0.6703	0.5534	0.646	0.5095

Robust standard errors are in parentheses.
[a]All regressions include regional dummy variables (East, North, West, South).
[b]The missing values in the 2007 physical investment per capita variable are replaced by the corresponding values in 2009 and 2013.
[c]Three urban regions, Saarbrücken, Erfurt, and Jena, are dropped from the 2007 regressions due to missing data.
$^{**}p < 0.01$. $^{*}p < 0.05$.

We use robust standard errors, and a battery of tests, including weak IV, over-identification, and endogeneity tests, have confirmed the validity of our IVs. The significant coefficients of functional polycentricity in the basic models of 2017 (models 3 and 7) suggest that districts situated in more polycentric urban regions exhibit higher economic productivity than those in monocentric regions, providing direct evidence of the borrowed size effect. A doubling of the degree of polycentricity contributes to an 8.05% (OLS) or 10.06% (2SLS) increase in districts' economic productivity. However, the 2007 coefficients (models 1 and 5) are insignificant, which suggests that not all types of districts are able to borrow size and that it is highly probable that one's better-off status comes at the expense of another's.

To determine the relationship between peripheries and urban cores, we examine the heterogenous effects of polycentricity on both of these geographies. The significant coefficients on the interaction terms in both years indicate that the impact of polycentricity on economic productivity differs significantly between peripheries and urban cores. While peripheries benefit from polycentricity, urban cores suffer losses. The OLS regression with the interaction term (model 4) reveals that a 100% increase in regional polycentricity in 2017 can contribute to a 10.55% increase in economic productivity for peripheries but also a decrease of 5.4% (10.55% minus 15.92%) for urban cores. Likewise, the 2SLS 2017 regression (model 8) indicates a 12.27% increase in economic productivity for peripheries and an approximately 0.5% decrease for urban cores, given a 100% increase in regional polycentricity. Similarly, the interaction terms in OLS and 2SLS models in 2007 (models 2 and 6) estimate an approximately 8% positive effect of polycentricity on economic productivity for peripheries and an 8%–12% negative effect for urban cores. For a robustness check, we further use the same functional form to test the heterogenous effects of morphological polycentricity (Poly_Morp and Poly_Ranksize) on peripheries and urban cores, and the regressions produce very similar results, as shown in Appendix 2.

Table 5. Cross-sectional regressions at the district level to test the effect of functional polycentricity (Poly_Fun) on economic productivity measured by GDP per capita in 2007 and 2017 using OLS and 2SLS estimators.

Variables (in logarithmic form)	OLS				2SLS			
	2007	2007	2017	2017	2007	2007	2017	2017
	(1) Poly	(2) Poly × Core	(3) Poly	(4) Poly × Core	(5) Poly	(6) Poly × Core	(7) Poly	(8) Poly × Core
Poly_Fun	0.0384 (0.0363)	0.0805* (0.0365)	0.0733* (0.0339)	0.1055** (0.0347)	0.0522 (0.050)	0.0825 (0.0481)	0.1006* (0.0473)	0.1227* (0.0504)
UrbanCore × Poly_Fun		−0.199** (0.0753)		−0.1592* (0.066)		−0.1608* (0.078)		−0.1272* (0.0646)
UrbanCore	0.3951** (0.051)	0.1956* (0.0814)	0.3336** (0.0501)	0.1759* (0.0729)	0.3935** (0.0489)	0.2326** (0.0876)	0.3295** (0.0437)	0.2097** (0.0772)
Population	−0.0732* (0.0348)	−0.0755* (0.0336)	−0.0702* (0.0324)	−0.0715* (0.0315)	−0.0728* (0.0336)	−0.0748* (0.0325)	−0.0688* (0.0278)	−0.0697* (0.0299)
Investment per capita[b]	0.1693** (0.0461)	0.1791** (0.0451)	0.1581** (0.0542)	0.1638** (0.0537)	0.1707** (0.0454)	0.1783** (0.0434)	0.1613** (0.0348)	0.1655** (0.0521)
Education	0.4663** (0.049)	0.4513** (0.0469)	0.4729** (0.0596)	0.4565** (0.0571)	0.4688** (0.0487)	0.4561** (0.0477)	0.4802** (0.0532)	0.4621** (0.0591)
Kleibergen-Paap *F*-statistics (Weak IV test)					157.495	83.688	137.144	85.628
Sargan-Hansen statistics (overidentification test)					0.616	1.866	0.024	0.618
Endogeneity test					0.053	0.100	0.543	0.030
State dummies[a]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.9138** (0.4589)	2.2876** (0.4529)	2.4056** (0.4348)	2.4635** (0.4224)	2.2318** (0.4594)	2.2733** (0.4426)	2.3732** (0.3632)	2.4288** (0.4121)
Observations[c]	230	230	250	250	230	230	250	250
R^2	0.7206	0.7326	0.6682	0.6778	0.7204	0.7309	0.6674	0.6754

Robust standard errors are in parentheses.
[a]All regressions include 13 state dummies. Notably, the city-state Berlin is merged into Brandenburg, the city-state Hamburg is merged into Schleswig-Holstein, and Bremen is merged into Niedersachsen.
[b]The missing values in the 2007 physical investment per capita variable are replaced by the corresponding values in 2009 and 2013.
[c]Observations dropped due to missing values include districts in urban regions of Erfurt and Jena, Aachen, and Reutlingen in 2007; and districts in Aachen and Reutlingen in 2017.
$^{**}p < 0.01$. $^{*}p < 0.05$.

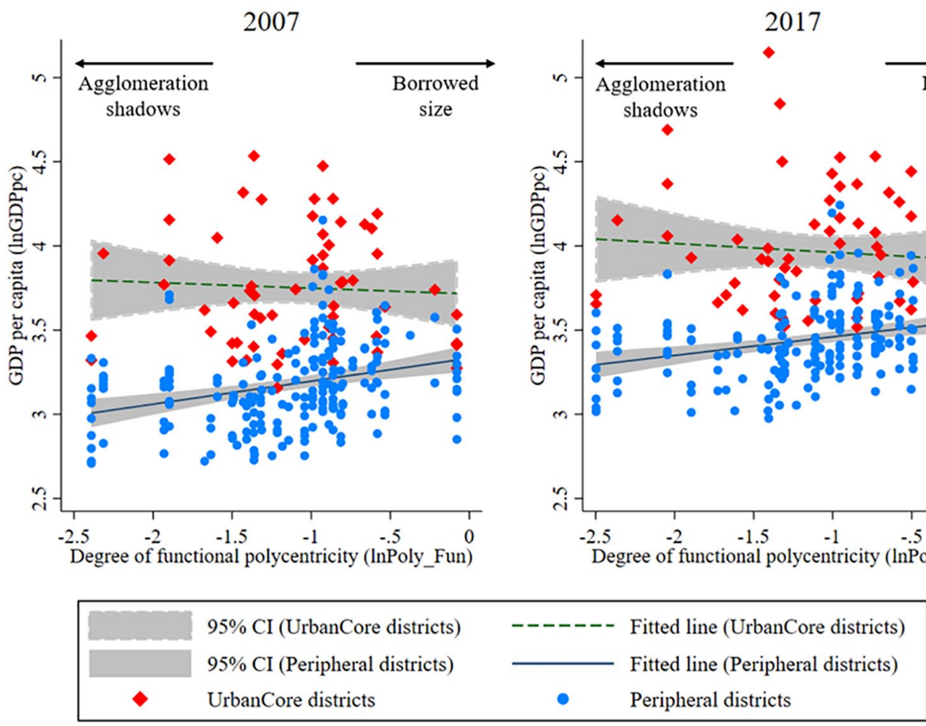

Figure 3. The scatterplots and corresponding fitted lines display the relationship between the degree of polycentricity and the economic productivity of peripheral districts and urban cores.

The results demonstrate that polycentric development produces a “win-loss” outcome between the peripheries and urban cores. That is, peripheries in polycentric regions can borrow size from the urban core, thereby enhancing economic performance; however, urban core(s) may suffer consequent economic losses due to the same effect, and potentially are disadvantage compared with their monocentric counterparts. Figure 3 illustrates the gains of peripheries and the loss of urban cores more intuitively. The peripheries fit a positive trend line as the degree of polycentricity increased, while the fitted line of urban cores displayed a moderately decreasing trend. The convergence between the two fitted lines as the degree of polycentricity increases suggests that the economic gaps between peripheries and urban cores have narrowed, ultimately resulting in more equitable urban regions. This trend may explain our result in sectional “Regression analysis for urban regions,” which suggests that polycentric development can effectively reduce regional economic disparities, as the effects of borrowed size outweigh agglomeration shadows in polycentric regions.

However, as the borrowed size only benefits the peripheries while exerting negative effects on urban cores within the same region, the economic productivity of the entire region is neutralized due to the existence of two countervailing forces. Similarly, the agglomeration shadows effect works the other way around: it benefits urban cores at the expense of the peripheries, as evidenced by the wider gaps between the two fitted lines as the degree of polycentricity decreases. Given that both effects result in winners and losers simultaneously, there exist no significant differences in economic productivity between polycentric regions that facilitate borrowed size effects and monocentric regions with agglomeration shadows.

Conclusions and discussion

This paper examines the influences of polycentricity on regional inequalities and economic productivity in German regions. Using three polycentricity measures, 2SLS estimators, and German urban regions as the appropriate regional delineation, we contribute several major findings to the theoretical and policy aspects of polycentric development.

First, the differences between measures of functional and morphological polycentricity in German urban regions are not as significant as those observed in other regions or countries. Functional polycentricity, generally speaking, displays a good fit with the morphological ones, and the different measures produce consistent results. This suggests that the German polycentric urban regions have not only maintained continual polycentricity in physical shapes but also exhibited a significant level of interconnectivity and multidirectional relations that produces functional polycentricity.

Second, we find that polycentric development can effectively reduce regional disparities for German urban regions, thereby achieving a more cohesive and balanced regional development as advocated by EU spatial planning policies. A similar conclusion was drawn by Meijers and Sandberg (2021) in a recent study that used panel models to analyze EU countries. Other studies conducted at regional scale, in the Czech Republic, Italy, and China, have suggested either insignificant or adverse effects of polycentrism on reducing regional disparities (Malý, 2016; Sun et al., 2019; Veneri and Burgalassi, 2012). We find that polycentric development can not simultaneously improve regional economic productivity, suggesting that the desired "win-win" scenario suggested by the ESDP remains elusive. Ouwehand et al. (2022) drew a similar conclusion in a pan-European study, as did Brezzi and Veneri (2015) in studying OECD countries, while Meijers and Burger (2010) found opposite effects in US metropolitan regions. Given the mixed results of polycentricity on both regional disparities and economic performance, we recommend further research be conducted within each European country to enrich the across-country comparison within the EU.

Third, a further investigation of the heterogeneous effects of polycentricity at the district scale suggested possible explanations for the failure to achieve simultaneous outcomes. Specifically, polycentric development produces a "win-loss" game between peripheries and urban core(s) within the same urban region. Peripheries develop at the expense of urban core(s), narrowing the economic gaps between peripheries and urban cores and creating more economically equitable regions. However, polycentricity does not improve the overall economic performance of the region, as the losses of urban cores cancel out the gains of the peripheries. Therefore, we argue that the borrowed size effect, facilitated by polycentric development, yields similar overall economic outcomes to the agglomeration shadow effect, as the latter benefits urban cores at the expense of peripheries, whereas the former operates in a reverse manner by bolstering peripheries at the expense of urban cores.

Polycentric development is clearly not a panacea to address various regional issues simultaneously. That said, spatial policies can profit from the results in attempting to balance simultaneous regional goals. Policymakers in monocentric regions may consider polycentric development as an effective way of minimizing regional economic disparities but may also be aware of its negative effect on urban cores. Meanwhile, policymakers should be prudent when considering polycentricity as a policy instrument to promote economic performance. Although our result has not suggested it is effective in regional economic policies, polycentric development might be effective when the gains of peripheries outweigh the losses of urban cores, which may be the case in certain urban regions.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Wenzheng Li https://orcid.org/0000-0003-2895-5434

Supplemental material

Supplemental material for this article is available online.

Notes

1. We made several minor changes in re-delineating the urban regions based on district boundaries to better measuring polycentricity and regional disparities. These include merging the small urban region Halle into the nearby urban region Leipzig, merging the independent city Salzgitter into the urban region Braunschweig, and merging the city Pforzheim into the urban region Karlsruhe.
2. The East includes the urban regions in the states of Thüringen, Brandenburg, Mecklenburg-Vorpommern, Sachsen, Sachsen-Anhalt. The North includes Niedersachsen, Schleswig-Holstein. The West includes Hessen, Nordrhein-Westfalen, Rheinland-Pfalz, Saarland. The South include Bayern and Baden-Württemberg.
3. The Germany local population to construct the instrumental variable is available at: https://leopard.tu-braunschweig.de/receive/dbbs_mods_00071017.

References

Alonso W (1964) *Location and Land Use: Toward a General Theory of Land Rent*. Cambridge, MA: Harvard University Press.

Baldwin R and Martin P (2004) Chapter 60. Agglomeration and economic geography. In: Henderson JV and Thisse JF (eds) *Handbook of Regional and Urban Economics*, vol. 4. The Netherlands: Elsevier, pp.2563–2608.

Baum-Snow N (2020) Urban transport expansions and changes in the spatial structure of US cities: Implications for productivity and welfare. *The Review of Economics and Statistics* 102: 929–945.

BMVBS (2006) *BMVBS (Bundesministerium für Verkehr, Bau und Stadtentwicklung) (2006): Leitbilder und Handlungsstrategien für die Raumentwicklung in Deutschland*. Verabschiedet von der Ministerkonferenz für Raumordnung am 30.06.2006. Berlin.

Boussauw K, Van Meeteren M, Sansen J, et al. (2018) Planning for agglomeration economies in a polycentric region: Envisioning an efficient metropolitan core area in Flanders. *European Journal of Spatial Development* 69: 1–26.

Brezzi M and Veneri P (2015) Assessing polycentric urban systems in the OECD: Country, regional and metropolitan perspectives. *European Planning Studies* 23(6): 1128–1145.

Capello R (2000) The city network paradigm: Measuring urban network externalities. *Urban Studies* 37(11): 1925–1945.

Capello R and Camagni R (2000) Beyond optimal city size: An evaluation of alternative urban growth patterns. *Urban Studies* 37(9): 1479–1496.

CEC (2004) *A New Partnership for Cohesion: Convergence Competitiveness Cooperation: Third Report on Economic and Social Cohesion*. Luxembourg: Office for Official Publications of the European Communities.

Ciccone A and Hall R (1993) *Productivity and the Density of Economic Activity*. w4313, April. Cambridge, MA: National Bureau of Economic Research.

Davoudi S (2003) European briefing: Polycentricity in European spatial planning: From an analytical tool to a normative agenda. *European Planning Studies* 11(8): 979–999.

Derudder B, Liu X, Wang M, et al. (2021) Measuring polycentric urban development: The importance of accurately determining the 'balance' between 'centers'. *Cities* 111: 103009.

ESDP (1999) *ESDP - European Spatial Development Perspective: Towards Balanced and Sustainable Development of the Territory of the European Union*. Luxembourg: Office for Official Publications of the European Communities.

EU Ministers (2020) *Territorial Agenda 2030. A future for all places*. Available at: https://ec.europa.eu/regional_policy/sources/docgener/brochure/territorial_agenda_2030_en.pdf (accessed 1 August 2022).

European Union (2011) *Territorial Agenda of the European Union 2020: Towards an Inclusive, Smart and Sustainable Europe of Diverse Regions*.
Faludi A (2005) Polycentric territorial cohesion policy. *Town Planning Review* 76(1): 107–118.
Fujita M and Thisse J-F (2002) *Economics of Agglomeration: Cities, Industrial Location and Regional Growth*. Cambridge: Cambridge University Press.
Gluschenko K (2018) Measuring regional inequality: To weight or not to weight? *Spatial Economic Analysis* 13(1): 36–59.
Green N (2007) Functional polycentricity: A formal definition in terms of social network analysis. *Urban studies* 44(11): 2077–2103.
Hall P and Pain K (2006) *The Polycentric Metropolis: Learning From Mega-City Regions in Europe*. Routledge.
Kloosterman RC and Musterd S (2001) The polycentric urban region: Towards a research agenda. *Urban Studies* 38(4): 623–633.
Krugman P (1991) Increasing returns and economic geography. *Journal of Political Economy* 99(3): 483–499.
Lee B (2007) 'Edge' or 'edgeless' cities? Urban spatial structure in U.S. metropolitan areas, 1980 to 2000. *Journal of Regional Science* 47(3): 479–515.
Lessmann C (2009) Fiscal decentralization and regional disparity: Evidence from cross-section and panel data. *Environment and Planning A: Economy and Space* 41(10): 2455–2473.
Li W, Sun B and Zhang T (2019) Spatial structure and labour productivity: Evidence from prefectures in China. *Urban Studies* 56(8): 1516–1532.
Li Y and Liu X (2018) How did urban polycentricity and dispersion affect economic productivity? A case study of 306 Chinese cities. *Landscape and Urban Planning* 173: 51–59.
Liu X and Wang M (2016) How polycentric is urban China and why? A case study of 318 cities. *Landscape and Urban Planning* 151: 10–20.
Malý J (2016) Impact of polycentric urban systems on intra-regional disparities: A micro-regional approach. *European Planning Studies* 24(1): 116–138.
Meijers E, Hoogerbrugge M and Cardoso R (2018) Beyond polycentricity: Does stronger integration between cities in polycentric urban regions improve performance? *Tijdschrift voor economische en sociale geografie* 109(1): 1–21.
Meijers E and Sandberg K (2008) Reducing regional disparities by means of polycentric development: Panacea or placebo? *Scienze Regionali* 7: 71–96.
Meijers E and Sandberg K (2021) Territorial cohesion, polycentrism and regional disparities: Revisiting an unsolved debate. In: Rauhut D, Sielker F and Humer A (eds) *EU Cohesion Policy and Spatial Governance*. Cheltenham: Edward Elgar Publishing, pp.127–141.
Meijers EJ and Burger MJ (2010) Spatial structure and productivity in US metropolitan areas. *Environment and Planning A: Economy and Space* 42(6): 1383–1402.
Meijers EJ and Burger MJ (2017) Stretching the concept of 'borrowed size'. *Urban Studies* 54(1): 269–291.
Meijers EJ, Burger MJ and Hoogerbrugge MM (2016) Borrowing size in networks of cities: City size, network connectivity and metropolitan functions in Europe: Borrowing size in networks of cities. *Papers in Regional Science* 95(1): 181–198.
Münter A and Volgmann K (2021) Polycentric regions: Proposals for a new typology and terminology. *Urban Studies* 58(4): 677–695.
Ouwehand WM, van Oort FG and Cortinovis N (2022) Spatial structure and productivity in European regions. *Regional Studies* 56(1): 48–62.
Parr J (2004) The polycentric urban region: A closer inspection. *Regional Studies* 38(3): 231–240.
Parr JB (2002) Agglomeration economies: Ambiguities and confusions. *Environment and Planning A: Economy and Space* 34(4): 717–731.
Parr JB (2008) Cities and regions: Problems and potentials. *Environment and Planning A: Economy and Space* 40(12): 3009–3026.
Phelps NA (2004) Clusters, dispersion and the spaces in between: For an economic geography of the banal. *Urban Studies* 41(5–6): 971–989.
Rauhut D and Humer A (2020) EU Cohesion Policy and spatial economic growth: Trajectories in economic thought. *European Planning Studies* 28(11): 2116–2133.
Roesel F (2022) The German Local Population Database (GPOP), 1871 to 2019. *Jahrbücher für Nationalökonomie und Statistik*. Epub ahead of print 19 August 2022. DOI: 10.1515/jbnst-2022-0046.

Rosenthal SS and Strange WC (2020) How close is close? The spatial reach of agglomeration economies. *Journal of Economic Perspectives* 34(3): 27–49.
Sun B, Li W, Zhang Z, et al. (2019) Is polycentricity a promising tool to reduce regional economic disparities? Evidence from China's prefectural regions. *Landscape and Urban Planning* 192: 103667.
Tabuchi T and Thisse J-F (2002) Taste heterogeneity, labor mobility and economic geography. *Journal of Development Economics* 69(1): 155–177.
Thomas R, Schmidt S and Siedentop S (2022) Toward comparative polycentricity scores: Assessing variations in regional delineation and subcenter identification. *Environment and Planning B: Urban Analytics and City Science* 49: 1597–1611.
Veneri P and Burgalassi D (2012) Questioning polycentric development and its effects. Issues of definition and measurement for the Italian NUTS-2 regions. *European Planning Studies* 20(6): 1017–1037.
Volgmann K and Münter A (2022) Understanding metropolitan growth in German polycentric urban regions. *Regional Studies* 56(1): 99–112.
Wang M, Derudder B and Liu X (2019) Polycentric urban development and economic productivity in China: A multiscalar analysis. *Environment and Planning A: Economy and Space* 51(8): 1622–1643.
Zhang W and Derudder B (2019) How sensitive are measures of polycentricity to the choice of 'centres'? A methodological and empirical exploration. *Urban Studies* 56(16): 3339–3357.

Appendix 1

Generating the measures of regional inequalities

We rely on the GDP per capita at the district scale to generate the measures of regional inequalities for each urban region. Specifically, the calculation of the Gini coefficient is shown as:

$$Gini = \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left|y_i - y_k\right|}{2m^2\overline{y}} \tag{A1}$$

where y_i is GDP per capita for district $i\left(i = 1,\ldots,m\right)$. m is the total number of districts in an urban region. $\overline{y}$ is the arithmetic average of the regional GDP per capita. The equations for calculating the coefficient of variations (Cov) and the population-weighted Gini coefficient follow the works by Gluschenko (2018) and Lessmann (2009).

Appendix 2

Table A1. Robustness check of the effect of polycentricity on economic productivity at the district level using 2SLS estimators.

Panel A: Robustness check using Poly_Morp				
	2007	2007	2017	2017
	(1) Poly	(2) UrbanCore × Poly	(3) Poly	(4) UrbanCore × Poly
Poly_Morp	0.0686 (0.0625)	0.1004 (0.0611)	0.1136* (0.0567)	0.1504* (0.0585)
UrbanCore × Poly_Morp		−0.1669* (0.073)		−0.2068** (0.0691)
UrbanCore	0.3937** (0.0489)	0.3098** (0.0582)	0.3310** (0.0439)	0.2345** (0.0539)
Panel B: Robustness check using Poly_Ranksize				
	2007	2007	2017	2017
	(1) Poly	(2) UrbanCore × Poly	(3) Poly	(4) UrbanCore × Poly
Poly_Ranksize	0.1257 (0.1142)	0.1823 (0.1105)	0.2037* (0.1029)	0.2614* (0.1056)
UrbanCore × Poly_Ranksize		−0.2916* (0.1316)		−0.3193** (0.1148)
UrbanCore	0.3929** (0.0490)	0.5675** (0.0909)	0.3307** (0.0442)	0.5316** (0.0836)

Robust standard errors are in parentheses. Regressions include all control variables.
**$p < 0.01$. *$p < 0.05$.