Does urban polycentricity contribute to regional economic growth? Empirical evidence from a panel of Chinese urban regions

Abstract: Research examining the economic effects of urban polycentricity remains inconclusive. We contribute to this debate by developing a longitudinal framework in which changes in polycentricity in Chinese urban regions are linked with changes in total factor productivity. While we find no evidence of urban polycentricity being conducive to economic growth, we observe that the relationship depends on population size and the interactions between cities. We also find that cities borrow size from nearby cities in large urban regions, contributing to regional economic growth. We use our findings to reflect on China's regional economic and urban development strategies.

Keywords: polycentricity, urban regions; productivity, borrowed size; China

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1 Introduction

There is a longstanding research tradition investigating the conceptual, analytical, and empirical connections between spatial structure and economic performance (e.g., Bailey & Turok, 2001; Lee & Gordan, 2007; Ouwehand et al., 2022). In this literature, the term 'polycentric urban regions' (PURs) has become a key concept (Derudder et al., 2022) and refers to a regional cluster of proximate, physically separate, but functionally interdependent cities that do not markedly differ in importance (Meijers, 2008). In addition to the frequent claim that urban polycentricity is an unfolding empirical reality in different parts of the world, the concept has also been adopted in regional territorial development plans in Europe (Davoudi, 2003), the United States (Nelson & Lang, 2018), Latin America (Fernández-Maldonado et al., 2014), and China (Wei et al., 2020). Much of this policy attention can be traced back to a variety of (alleged) virtuous effects that are sometimes attributed to PUR-formation, including heightened economic productivity (Wang et al., 2019), lower environmental emissions (Burgalassi & Luzzati, 2015), and enhanced social cohesion (Davoudi, 2003).

Despite increasing attention in research and policy circles, there remains much uncertainty about the presence and the extent to which these virtuous effects play out in PURs. Economic effects, in particular, have been frequently researched. Some studies found that polycentric spatial structure has no direct impact on regional economic performance (see Ouwehand et al. (2022) for a pan-European analysis and Veneri and Burgalassi (2012) for an Italian case study). Others have found that more polycentric configurations tend to be associated with higher regional productivity (see Kwon and Seo (2018) and Wang et al. (2019) for analyses in South Korea and China, respectively). And finally, some studies also came to the opposite conclusion (see Huang et al. (2019) in their case study of the Beijing-Tianjin-Hebei region). Taken together, results are clearly inconclusive, and there is a need for more robust evidence on the putative economic effects of polycentric urban development in regions.

One possible reason for the diversity in empirical findings is using different analytical frameworks when measuring *urban polycentricity* and/or *economic effects*. Other operational choices may lead to different outcomes and may include some of the following elements:

(1) the definition and operationalization of polycentricity (Derudder et al., 2022; Thomas et al., 2022; Bartosiewicz & Marcinczak, 2020; Zhang et al., 2019);
(2) the selection of economic performance measures, ranging from labour productivity (LP) (Wang et al., 2019; Meijers & Burger, 2010) and per capita income (Brezzi & Veneri, 2015) to employment growth (Lee & Gordan, 2007), regional GDP (Veneri & Burgalassi, 2012) and total factor productivity (TFP) (Ouwehand et al., 2022);
(3) the methods used to address endogeneity issues, ranging from instrument variables (Meijers & Burger, 2010) and time lags for the explanatory variables (Wang et al., 2022) to dynamic panel models (Huang et al., 2020); and
(4) the kind of data (sectional or panel) used in longitudinal research designs. However, longitudinal approaches have been rare up till now (exceptions include Deinema et al. (2013) and Giuliano et al. (2019)).

To date, most research has focused on the impact of different analytical approaches to urban polycentricity (Meijers et al., 2018). Significantly less attention has been paid to: the selection of economic indicators (with Ouwehand et al. (2022) as an exception), how to address potential endogeneity problems, and the relevance of adopting a longitudinal framework. Against this background, we contribute to the ongoing debate on the relationship between polycentric spatial structures and regional economic performance by focusing on this unfolding relationship in Chinese urban regions between 2005 and 2017.

Our study extends the literature on several fronts. First, we build on approaches (total factor productivity (TFP)) that have only very recently been adopted in this field (Ouwehand et al., 2022) to measure regional economic performance. Compared to LP, TFP captures productivity conditional not only on available labour inputs but also on other factors of production, such as physical and human capital (Beugelsdijk et al., 2018). While this has recently been argued to be a more accurate measure of productivity (Cortinovis & Van Oort, 2019; Ouwehand et al., 2022), TFP has only been adopted in a handful of predominantly European-focused analyses. Second, we develop a longitudinal framework linking PUR-formation and economic effects across space *and* time. In doing so, we extend the work of Liu et al. (2018) and Wang et al. (2019), who documented the presence of PURs in China but either focused on a handful of urban regions or limited their analyses to a given point in time. And third, as part of our longitudinal research design, we implement the emerging technique (see Harari, 2020) of time-varying instrumental variables analysis to capture potential endogeneity in the relationship between polycentric regional structures and economic performance.

The remainder of this paper consists of five sections. The first section reviews the literature on measuring regional economic growth, the potential impact of polycentric structures on regional economic growth, and polycentric development in China. Second, drawing on this review, we specify a set of hypotheses guiding our research. Third, we outline our methodological framework, after which we proceed with a fourth section that reports our main findings. Fifth, we conclude the paper with an overview of our main results, policy implications, and main avenues for future research.

2 Literature review

2.1 Measuring regional economic growth

'Economic growth' is a container term, with some elements being more pertinent than others depending on the research purpose. According to Ouwehand et al. (2022, p. 54), previous studies have not always clearly motivated their choice of economic growth indicators. Taken together, studies have assessed the alleged economic benefits of PURs through three lenses. The first group studies the spatial pattern of wages (Meijers, 2013). The key idea is that if workers and firms are mobile and wages differ across space, higher wages must reflect productive advantages in PURs (Puga, 2010). A second group analyzes urban growth indicators such as population and employment growth (Lee and Gordan, 2007). The rationale here is that economic activities will locate elsewhere if drawbacks surpass benefits (Wheeler, 2003) so that the geographies of urban population growth reflect the interplay between agglomeration economies and diseconomies. A third group of studies focuses on productivity levels across space. It has been argued that productivity represents 'the most direct' (Puga, 2010, p. 204) way of measuring the size of agglomeration economies.

This last approach has arguably been most commonly pursued in the literature, often focusing on LP measured as output per worker. An advantage of this approach is that the data sources needed to calculate these measures are easy to access (Beugelsdijk et al., 2018) while interpreting the results is straightforward. However, some have argued that this approach adopts a narrow view of agglomeration economies (Puga, 2010), as LP only considers the role of labour input. Other production factors, such as human and physical capital and technological progress, are also important factors for explaining economic growth. Still, these are either not included or listed as exogenous control variables in regression models. Discarding these elements might lead to an upward bias in the estimated effects of polycentricity (Moomaw et al., 1981; Puga, 2010).

An alternative approach to measuring regional economic growth is total factor productivity, defined as the share of output not explained by the number of inputs used in production (Comin, 2010). This has been argued to be a more accurate measure of productivity (Cortinovis & Van Oort, 2019), and 'the change from labour productivity to a TFP measure (…) can be seen as an important methodological improvement' (Ouwehand et al., 2022, p. 53). This improvement can be traced back to several complementary factors. First, TFP is considered more comprehensive as it considers additional factors like technology transfers, knowledge spillovers between firms, and the interaction and sharing of ideas, skills, and experiences among people (Otsuka, 2017). Second, TFP also captures the overall complexity of the production process. In the computation process, the regionally varying input factors (e.g., capital and labour endowments) are already incorporated in the computation of TFP. The TFP level solely reflects the intensity with which different production inputs are utilized and combined (Beugelsdijk et al., 2018). Building on these comparative advantages, in this paper, we adopt the TFP measure to describe regional economic growth.

2.2 Polycentricity and regional economic growth

Several theoretical frameworks link the formation of PURs to regional economic performance. From a first perspective, PURs can lead to what Parr (2002) has called 'regional externalities.' This concept builds on 'agglomeration economies' (Rosenthal & Strange, 2004), referring to the benefits associated with the spatial clustering of population and economic activities in terms of labour market pooling, shared inputs, and knowledge spillovers. The spatial range within which agglomeration economies occur is not necessarily confined to the borders of 'cities' but can also be shared across proximate and well-connected cities (Van Oort et al., 2010). Such a 'regionalization' of agglomeration externalities has been recently conceptualized and discussed by researchers using the term 'network externalities' (Capello, 2000), which hypothesizes that by participating in a regional city network, cities can exploit advantages from complementary relationships and synergies in cooperative activities.

This focus on 'urban network externalities' has recently been further elaborated by revisiting Alonso's (1973) concept of 'borrowed size': due to physical proximity and increased accessibility to large cities, smaller and medium-sized cities can 'borrow' some of the functions from neighbouring large cities situated in the same PUR (Burger et al., 2015). By virtue of this 'borrowed size' effect, PURs as a whole may realize additional agglomeration effects, given that shared size allows for reaching higher thresholds of agglomeration economies (Van Meeteren et al., 2016). However, 'borrowed size' effects can be mirrored by 'agglomeration shadow' effects: due to competition effects, the growth of smaller cities may be inhibited by larger cities, so that PUR-formation entails poorer economic performance (Burger et al., 2015). The two effects are often deemed 'two sides of the same coin' (Ibid. p. 1093). As both 'borrowed size' and 'agglomeration shadow' effects describe possible outcomes of interactions between individual cities in a region, the overall impact of polycentricity on regional economic growth can be hypothesized to depend on the relative balance between both effects.

The second process can be related to agglomeration diseconomies being 'borrowed' between nearby cities in a PUR. Generally, agglomeration diseconomies or the costs associated with increased competition for scarce resources due to co-location, such as high land prices and wages, traffic congestion, and air pollution exposure, tend to increase with size. Evidence from Capello and Camagni (2000) suggests that small and medium-sized cities have a greater capacity to keep these economic, social, and environmental costs under control. Building on the idea that agglomeration diseconomies remain spatially constrained at the local scale while agglomeration economies are regionalized (Meijers, 2013), polycentric spatial structures are often hypothesized to have advantages in providing a balance between agglomeration economies and diseconomies.

Third, despite the consensus that regional externalities 'exist', it has been argued that their extent may depend on cities' and regions' overall size (population/territorial scale) . Evidence from the United States suggests that less populated urban regions benefit more from polycentricity (Meijers & Burger 2010). In the European context, polycentricity has been found to have no significant effects in urban regions with large(r) populations (Ouwehand et al., 2022). Besides this, several other size factors may influence the hypothesized impact of PURs on economic performance. For example, increasing distances between cities in large PURs may entail logistical barriers (Liu et al., 2016) or reduce economic advantages related to social interaction in cities, such as face-to-face contact (Storper, 2013). Meanwhile, in smaller PURs, cities tend to be connected more strongly when compared to larger ones, where the core cities are usually large enough to function independently (see Meijers and Burger (2010)).

Taken together, this leads us to the following hypotheses:

H1: A higher degree of urban polycentricity is conducive to regional economic growth.

H2: The extent to which polycentricity contributes to regional economic growth depends on the relative balance between 'borrowed size' and 'agglomeration shadow' effects.

H3: The impact of polycentricity on regional economic growth diminishes as urban population size increases.

2.3 The Chinese context: PURs, planning, and governance

The formation of PURs in Western Europe can be explained by a broadly similar set of economic logics (agglomeration, networking, and globalization) (Camagni, 2015; Hoyler et al., 2008; Lüthi et al., 2010). However, the European experience, particularly how PURs are invoked in planning discourse, does not always fit the Chinese context very well (Li et al., 2022) because urban development in China is very different, 'both economically, but above all, politically' (Hamnett, 2020, p. 2). Plans for polycentric urban development have gained momentum in China's planning praxis, incorporating the concept at different geographical and governance scales (Cheng & Shaw, 2017). This planning interest coincides with an emerging research interest in PUR-formation in China, often focusing on the Yangtze River Delta (Li & Wu, 2018), the Pearl River Delta (He et al., 2021), and Beijing-Tianjin-Hebei (Huang et al., 2020). Most of these studies focus on one specific urban region and therefore do not allow comparative approaches. A notable exception is a study by Wang et al. (2019), who analyzed the economic impact of urban polycentricity across all major urban regions based on a cross-sectional dataset. Here we adopt a longitudinal research design to extend the research of Wang et al. (2019).

Significantly, different governance levels may be associated with different economic impacts in the Chinese context. PURs in China need to be understood in the context of its specific planning regime, in which top-down and bottom-up processes intersect (Zhang et al., 2019). The former refers to planning initiatives installed by the central government, while the latter is created through cooperation between local governments. The central state uses a regional perspective to promote cross-jurisdictional coordination and boost regional economic growth. However, the implementation of regional strategies is challenging. It has been confronted, as local governments often prioritize their interests rather than promote cooperation based on alleged regional interests (Li & Wu, 2018). Without economic incentives that might stimulate these cooperations, the on-the-ground development of PURs may differ from the concept initially envisaged by the central state.

In operational terms, we aim to capture this process by looking at (i) regions' position in the administrative hierarchy and (ii) regions' geographical location (coastal versus inland China). First, the dispersal of power or authority from the central state (decentralization) is more prominent in urban regions that are higher in the administrative hierarchy. Specifically, 'National' URs, such as Beijing-Tianjin-Hebei, have the highest level of local autonomy and level of decentralization, followed by 'regional' URs, such as the Shandong Peninsula and 'sub-regional' URs, such as Central Shanxi (Fang et al., 2017). With more autonomy passed onto the local governments in National URs, they can be assumed to have better information on how to allocate resources efficiently, even though they are also more likely to be susceptible to local vested interests (Bardhan & Mookherjee, 2000; Wang et al., 2013). In other words, they are better positioned to provide public goods and services that more closely meet local needs (Li & Wu, 2018). In contrast, in regional/sub-regional URs, a more directive approach of the central government, encouraging the formation of a regionally coordinated economy, may be less flexible and adjustable. Consequently, URs at higher administrative hierarchies may have more capacity to exploit positive externalities by stimulating cooperation among cities.

Second, the peculiarities of the Chinese context can be captured by URs' geographical location. Guo and Minier (2021), and with them many other researchers, showed that there have been significant economic differences between coastal China and inland regions. These differences are correlated with preferential policies (e.g., tax incentives and migration policies to attract talent) implemented in coastal regions. Cities in these regions interact more intensively with foreign investors and among themselves, resulting in stronger links between several cities and possibly more polycentricity (Chen et al., 2021). These arguments also surface in debates on the effect of 'place-based policies' on local economic development in China (Koster et al., 2021; Alder et al., 2016). This could be a vital factor confounding our observations regarding the influence of polycentricity on TFP. However, it is challenging to identify clear-cut measures of 'place-based policies' across a very diverse China. We address this difficulty by comparing urban regions based on their geographic location, using it as a proxy to capture the variation of local policies partly rooted in their geographical proximity to the coast.

Taken together, our fourth and fifth hypotheses are:

H4: The position of urban regions in the administrative hierarchy in China's planning system influences polycentricity's impact on regional economic growth.

H5: Urban regions in coastal China exhibit different patterns regarding polycentricity's influence on the economy compared to inland China.

3 Research area, Data, and Methodology

3.1 Research area

Our analysis focuses on the nineteen urban regions identified in China's 14th Five-Year Plan (2021-2025) (Figure 1). These urban regions are relevant to China's territorial development strategy. Although they collectively only account for 29% of the national land area, in 2017, they captured 68% of the total population and 83% of the gross domestic product (GDP). In the 14th National Plan, these urban regions (URs) are divided into five national URs, eight regional URs, and six sub-regional URs. Among them, six URs are located in coastal China, and thirteen URs are located in inland China[1]. More detailed information about these URs is presented in Appendix A.

3.2 Data

Our research uses a range of complementary datasets. First, the LandScan™ High-Resolution Global Population Dataset (2005–2017) presents the global population distribution in 1 km^2 grids. Second, socio-economic data at the prefecture level, such as GDP, foreign direct investment, etc., are derived from the China City Statistical Yearbooks, the China Urban database, and the China Provincial Statistical Yearbooks (2005–2017). Third, as data for twelve autonomous prefectures are not documented in these yearbooks, we extracted them separately from Statistical Bulletins. Due to

[1] Among them, BBW UR in Guangxi province is not included, as not all boundaries are coastal, and this UR shares a border with Vietnam.

statistical definition issues, data for four cities are missing for several years[1]. We employed linear interpolation techniques to address this issue.

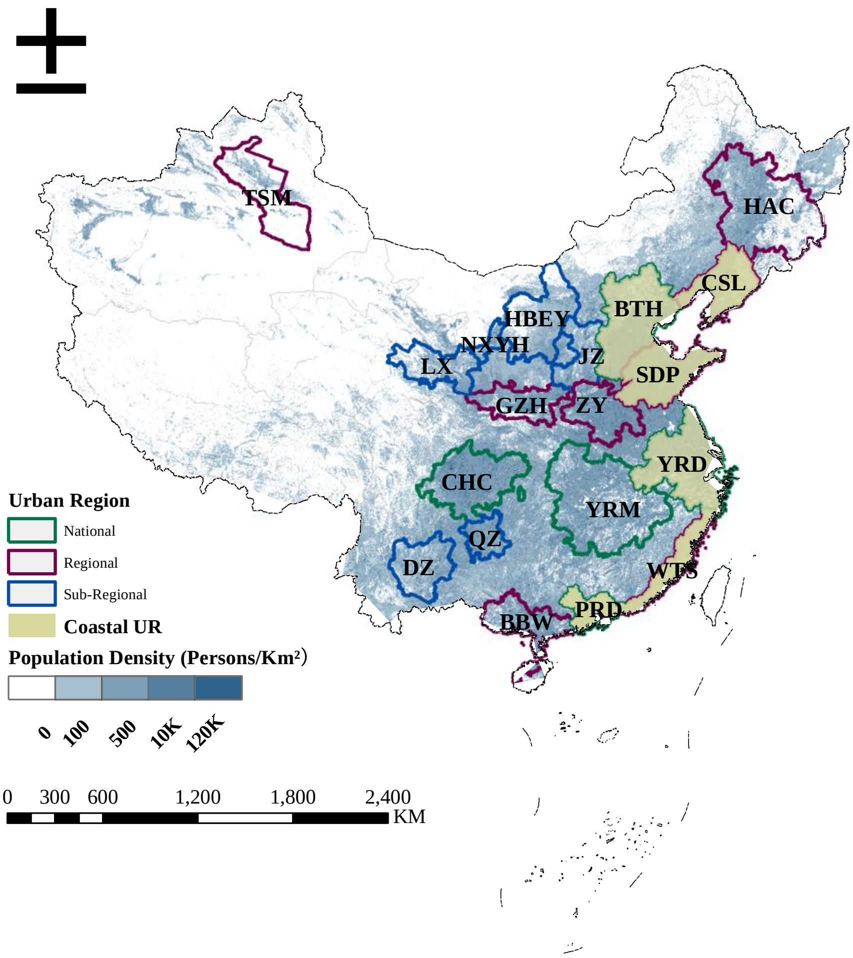


Figure 1. Location of the 19 urban regions identified in the 14th National Plan

3.3 Methodology

3.3.1 Operationalization of variables

(1) Measuring morphological polycentricity

We construct a polycentricity index in two steps: (1) we develop a set of population centres as our units of analysis, after which (2) we use the standard deviation method to assess the degree to which these centres exhibit a morphologically polycentric pattern (Green, 2007).

First, population centres are defined as significantly denser clusters than their surrounding areas. Drawing on the LandScan™ population dataset, we create a density file for individual cities, in which individual grids are ranked based on population density. Following Liu et al. (2018), we set a density cut-off at the city's 95-percentile gridded population and select the 5% most densely populated grids. In the second step, grids that are eight-adjacent to each other are

[1] The autonomous prefectures cities with incomplete data include Xiangyang (2005-2009), Hong Kong (2005-2017), Bijie (2005-2017) alongside nine other cities.

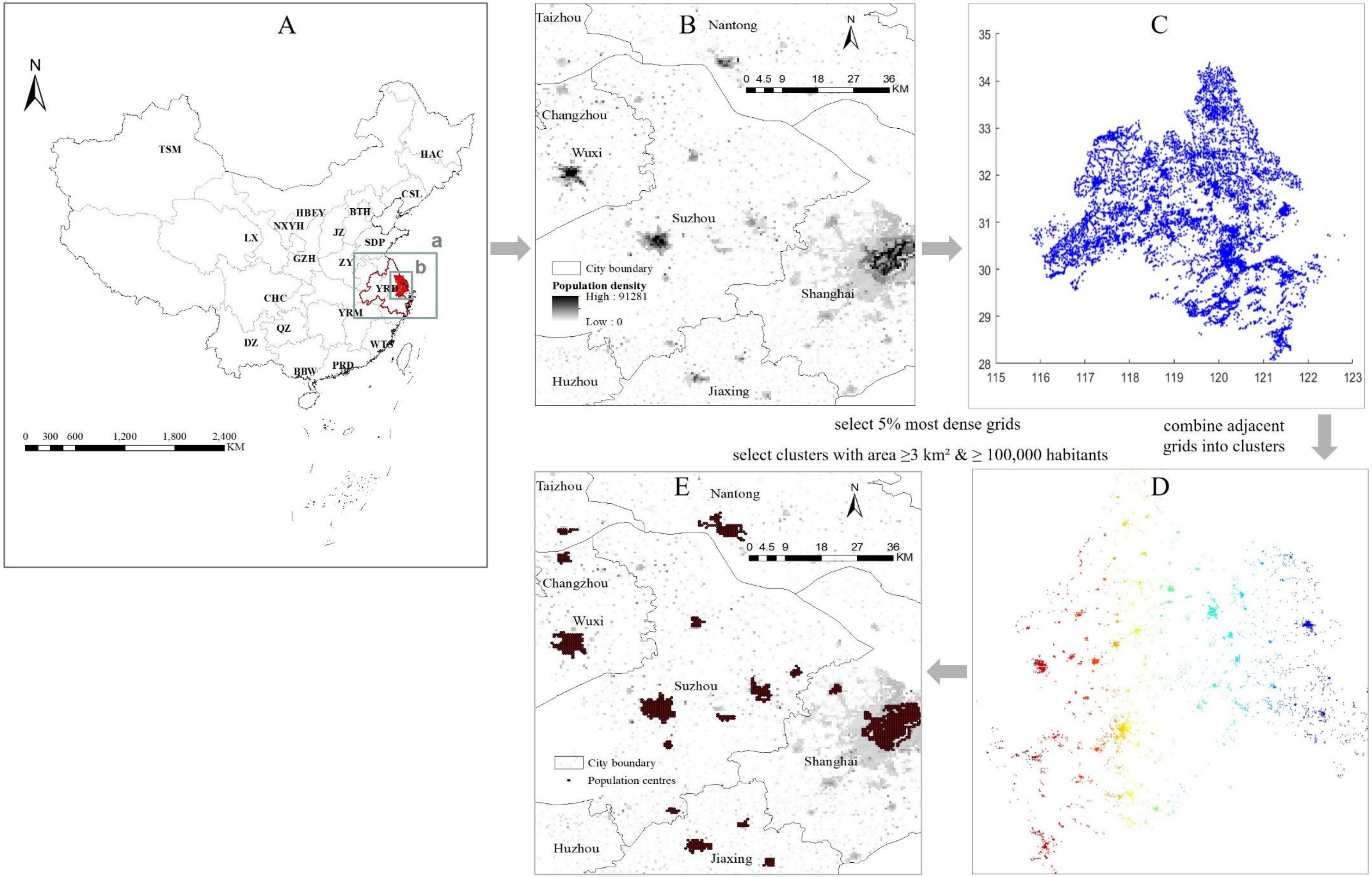
combined into clusters. In line with Liu et al. (2018), we retain those clusters covering at least 3 km² and containing more than 100’000 inhabitants[3] (Figure 2). The total population of these clusters within individual cities is calculated to denote cities’ ‘importance.’

Second, we calculate a polycentricity index as follows:

$$Poly = 1 - \frac{\sigma_{obs}}{\sigma_{max}} \quad (1)$$

where *Poly* indicates the degree of polycentricity of an urban region; σ_{obs} is the standard deviation of the ‘importance’ of individual cities within an urban region; and σ_{max} represents the maximum possible standard deviation, defined as the standard deviation in a hypothetical two-city urban region where one city has no population. *Poly* ranges from 0 (no polycentricity) to 1 (an ideal-typical polycentric urban region where all cities are equally large).

[3] The conditions we set to determine ‘population centres’ are tailored to the Chinese context. We set the criterion (over 3 km²) given that some newly-planned towns in some Chinese cities are surrounded by areas with low population density and weak infrastructure. While they may be regarded as population centres in absolute terms, they are not qualified as ‘actual’ population centres due to their modest influence on their surroundings and should therefore be filtered out (Li and Liu, 2018). Second, according to ‘The Rule on the Organization of Urban District Offices in China’ (2018), districts with populations of more than 100,000 should establish Street Offices. These street offices are responsible for the task prescribed by the municipal or district government (e.g., construction of economic development zone) (Ma and Wu, 2004). So, each street often has a concentrated area and the population density of the boundary region between streets is often relatively lower. Therefore, if the urban population in the district reaches 100,000, it might indicate the emergence of new population centres.



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0 300 600 1,200 1,800 2,400
KM
B
Taizhou
Nantong
0 4.5 9 18 27 36
KM
Changzhou
Wuxi
Suzhou
City boundary
Population density
High : 91281
Low : 0
Shanghai
Huzhou
Jiaxing
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select 5% most dense grids
combine adjacent
grids into clusters
select clusters with area ≥3 km² & ≥ 100,000 habitants
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Taizhou
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0 4.5 9 18 27 36
KM
Changzhou
Wuxi
Suzhou
City boundary
Population centres
Shanghai
Huzhou
Jiaxing

Figure 2. Process of identifying population centres in cities as illustrated by the example of cities in the Yangtze River Delta
(using ArcGIS and MATLAB software). Figures C and D cover the entire YRD region (i.e., region a in Figure A), while Figures B and E represent only part of the YRD region (i.e., region b in Figure A).

(2) Measuring economic efficiency

We then measure TFP using the nonparametric Malmquist index in data envelopment analysis (DEA) (Menegaki & Angeliki, 2013). This approach treats each urban region in each year as a decision-making unit (DMU) and represents how well a DMU processes inputs into outputs (Fujita & Ogawa, 1982). The model can be mathematically represented as follows:

$$M_0^{t+1}(x_0^t, y_0^t, x_0^{t+1}, y_0^{t+1}) = \left[\frac{D^t(x_0^{t+1}, y_0^{t+1})}{D^t(x_0^t, y_0^y)} * \frac{D^{t+1}(x_0^{t+1}, y_0^{t+1})}{D^{t+1}(x_0^t, y_o^t)}\right]^{\frac{1}{2}} \tag{2}$$

Where the Malmquist index M_0^{t+1} indicates the degree of TFP, D^t and D^{t+1} represent the distance functions of years *t* and *t+1*, defined as the maximum reduction of inputs when maintaining the output level. x_0^t and x_0^{t+1}represent input factors (fixed capital stock and labour force). y_0^t and y_0^{t+1} represent the GDP of urban regions. The fixed capital stock denotes the total value of capital assets, estimated based on the perpetual inventory method; the labour force is expressed as the total number of employed persons across all sectors in an urban region. The equation denotes how economic efficiency changes: a TFP greater, equal to, or smaller than 1, respectively indicates rising, unchanged, or decreasing levels of efficiency (See Appendix B for more details on measuring TFP).

3.3.2 Model

(1) Regression model

We use a fixed-effects panel data model (FE) to quantify the possible influence of polycentricity on the TFP of urban regions. Equations (3), (4), and (5) are used to test hypotheses *H1, H2,* and *H3*, respectively. Subsequently, we divide the full samples into sub-samples according to regions' (i) administrative governance level and (ii) geographic location and re-apply equations (4) and (5) to test hypotheses *H4* and *H5*, respectively.

$$LN(TFP_{it}) = \delta + \alpha POLY_{it} + \beta Y_{it} + \gamma_i + \delta_i + \varepsilon_{it} \tag{3}$$

$$LN(TFP_{it}) = \delta + \alpha POLY_{it} + \beta BOR_{it} + \theta {BOR_{it}}^2 + \vartheta Y_{it} + \gamma_i + \delta_i + \varepsilon_{it} \tag{4}$$

$$LN(TFP_{it}) = \delta + \alpha POLY_{it} + \beta POP_{it} * POLY_{it} + \vartheta Y_{it} + \gamma_i + \delta_i + \varepsilon_{it} \tag{5}$$

Where TFP_{it} is the total factor productivity of urban region *i* in year *t*, $POLY_{it}$ is the degree of polycentricity, BOR_{it} captures the net effects of borrowed size and agglomeration shadows, with its squared term ${BOR_{it}}^2$ added to test whether the effect is nonlinear, POP_{it} represents the total population, Y_{it} denotes a set of control variables (see below), γ_i is the time-fixed variable, δ_i is the individual fixed effect, ε_{it} is the random error term of the model, and α, β, θ, ϑ are the parameters to be estimated. In line with Meijers and Burger (2010), the variables were log-transformed to ensure a linear form.

We first calculate the borrowed size effect (BOR_{it}) at the level of individual cities, and then aggregate it regionally. Based on Camagni et al. (2017), 'borrowed size' is measured using the spatially lagged population living in neighbouring cities divided by distance. A positive coefficient of BOR_{it} on TFP indicates that the total borrowed size effect dominates the total agglomeration shadow effect:

$$BOR_{it} = \sum_{j}^{n} \frac{POP_{it}}{W_{ij_t}} \tag{6}$$

Where i and j represent two cities within an urban region, W_{ij} is the n x n distance weight matrix formalizing the spatial dependence between all cities, and POP_{jt} represents city j's total population in year t.

We also add a set of control variables Y_{it} in our regression models. First, human capital plays a vital role in the production function of a region (Ouwehand et al., 2022). We use the ratio of students who received higher education to the total population as a proxy. Second, there is the informatization level, which refers to the effectiveness with which a regional economy utilizes information technology (Huang et al., 2020). We proxy this by using the government expenditure on postal and telecommunications services. Third, rapidly innovating and growing industries often display higher productivity levels and can thus be an important factor affecting regional economic growth (Ouwehand et al., 2022). Consequently, we introduce the relative size of the tertiary industry in a region, calculated as the ratio of the output in the tertiary industry to that in the secondary industry. Fourth, foreign direct investment (FDI) can, among other things, facilitate the introduction of advanced technologies and thus contribute to differences in productivity levels between regions (Huang et al., 2020). The ratio of total FDI to GDP is included to proxy this factor. Fifth and finally, governments exert institutional power and adopt different market intervention strategies (Wang et al., 2019), which is controlled for as the ratio of government expenditure to revenue. The descriptive statistics of these variables are reported in Appendix C.

(2) Instruments to tackle endogeneity effects

Analyses of how polycentricity affects TFP are prone to potential endogeneity issues: spatial organization may be a consequence rather than a cause of economic performance (Meijers & Burger, 2010). For instance, urban regions with a higher economic performance generally generate more production factors, which may attract more firms, provide more employment opportunities, and subsequently influence how population is organized and distributed across space.

The most common technique to deal with endogeneity effects is adopting instrumental variable (IV) regression (Meijers & Burger, 2010). Here, a first-stage regression is conducted using the endogenous variables as the dependent variable, after which the predicted values from the regression are saved and subsequently used as new variables. In a second-stage regression, the independent variables are regressed on the newly generated. A valid instrumental variable should be (1) correlated with the (potentially) endogenous variables and (2) uncorrelated with dependent variables. In the PUR literature, a wide range of instrumental variables have been proposed, including elements of the natural environment (Wang et al., 2019), distance from districts to urban centres (Zhang et al., 2017), and historical levels of polycentricity (Ouwehand et al., 2022). Among these options, instruments using local features are time-invariant, whereas historical polycentricity can still be related to the contemporary, unobserved heterogeneity that accounts for present performance (Li & Du, 2021).

As this paper uses panel data, we develop a time-varying instrument. We follow Li and Du (2021), who recently used historical, urban shapes-predicted levels of polycentricity to discuss the impact of polycentricity on innovation. Their approach is inspired by Harari (2020), who assumes that firms and jobs may respond to deteriorating urban shapes by dispersing throughout cities and forming new centres around job locations, suggesting a possible predictive power of urban shapes on polycentricity. The method in Li and Du (2021) is one of the few attempts in the polycentricity literature to investigate the effectiveness of urban geometry as IVs, albeit it is only applicable for studies at a given time. To exploit temporal variation in urban shapes, we incorporate a time-varying characteristic - the predicted expansion path of an urban area - to construct IVs. As Harari (2020) hypothesized, as cities' expansion in land area reflects population growth without geographical constraints (e.g., water bodies or steep terrain), the urban area can be assumed to develop circularly with the same population density in all directions. In other words, the variation in these geographical constraints leads to a departure of this circular expansion, and the instrument captures this variation. Notably, such geographical constraints are less likely to affect economic performance (Wang et al., 2019).

To guarantee this instrument is strictly exogenous, we use an alternative dataset, the light intensity data on China's territory from the Defense Meteorological Satellite Program Operational Line-Scan System (DMSP/OLS) Night-time Lights, to implement the instruments. This is a series of night-time satellite imaginary recordings of the yearly intensity of earth-based lights, measured by a value ranging from 0 to 63, with a resolution of approximately 1 square kilometre. The procedure consists of the following five steps:

Step (1): Detecting an 'urban area' in 1992. We first overlap the city centroids (gravity centres) with the night-time data and then identify the spatially contiguous[4] light pixels surrounding the city coordinates above a threshold of 45 as the urban area. The threshold choice is based on the study of Du and Zhang (2019), who use night-time data to map historic urban areas. Panel A (Figure 3) illustrates how we delineated the urban area of Qinhuangdao in 1992.

Step (2): Identifying the 'potential' urban area. We draw a minimum bounding circle around the 1992 urban area. The land within this circle not occupied by water bodies and not on steep terrain is considered 'developable.' We define the developable land as 'potential footprint,' coloured green in panel B (Figure 3).

Step (3): The calculation of urban shape metrics. The shape metrics toolbox in ArcGIS is employed to calculate four urban shape indexes (cohesion index, proximity index, spin index, and range index)[5] for each 'potential footprint.' These indexes explain to what extent the urban shape deviates from a circle (a more detailed illustration of how these indexes describe the polygon features of urban areas can be found in Hararri (2020).

Step (4): The projection of the radius of the urban area. Following Harari (2020), assuming the city's population continued to grow from 1992 to 2005, we build a regression model and use it to predict the 2005-2017 populations (the steps involved are outlined in Appendix D). Using a mechanical predicted population growth is essential since the city's actual growth path would be endogenous[6]. Assuming the population density remains consistent at its 1992 level, an urban area will grow in a circle without geographical obstacles as the population increases (Harari, 2020), which allows generating the urban area and its radius. The 'potential footprints' within the predicted radii in

[4] The extraction of contiguous pixels is based on the 8-connectivity rule.

[5] The cohesion index denotes the average indexes between all pairs of interior points in an urban area; the proximity index denotes the average distance from all interior points to the centroid of the urban area; the spin index is the average of the square of the distances between all interior points and the centroid of the urban area; the range index is the maximum distance between two points on the perimeter of the urban area.

[6] The estimation of the urban area in response to growth of urban population may be confounded by underlying city-specific trends, potentially driven by the initial conditions (i.e., the base situation in 1992). Nevertheless, controlling the projected historical population growth the 1992-2005 through the urban area instrumented partially addresses this concern, as it allows changes in city shapes to only affect the deviations from the city's long-run path.

panels C and D (Figure 3) represent the area Qinhuangdao would occupy in 2005 and 2017, respectively. We then calculate the urban shape metrics for these 'potential footprints' each year.

Step (5): The predicted polycentricity. Harari (2020) pointed out that jobs and firms may respond to deteriorating urban shapes by forming subcentres closer to the workers and clients, indicating a plausible predictive power of urban shapes on polycentricity. We used the 1992 polycentricity, the 1992 urban shape indexes, and the urban shape indexes in 2005-2017 to project polycentricity levels in 2005-2017. The variation in polycentricity captured by this time-varying instrument is thus induced by geography interacting with mechanically predicted city growth. The four indices lead to four predicted polycentricity levels (four instruments), with their effectiveness reported in Appendix F.

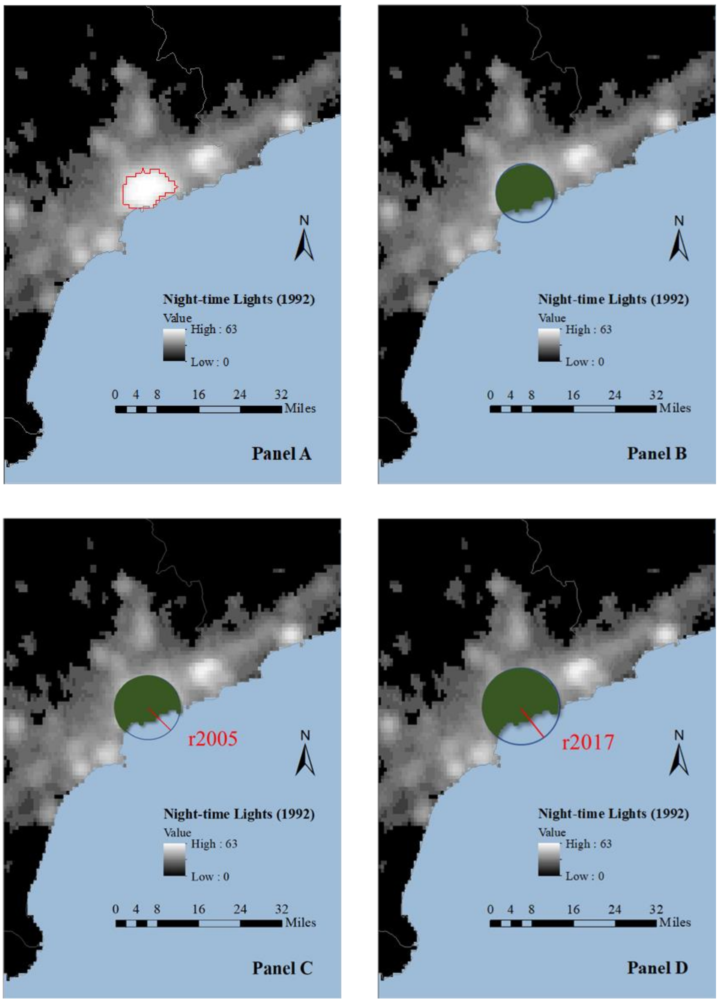

Figure 3. The procedure to construct panel instruments for polycentricity (Panel A indicates the urban area of Qinhuangdao in 1992; Panel B illustrates the potential extent of Qinhuangdao occupied in 1992; Panels C and D show the possible space Qinhuangdao would have occupied in 2005 and 2017, respectively, if it grows circularly from the centre outwards).

(3) Dealing with econometric issues

Before presenting our empirical results, we must also deal with the standard range of econometric issues. The panel unit test results suggest stable relationships between variables (Appendix E). We then assessed three common econometric issues in multivariate regression: multicollinearity, heteroscedasticity, and autocorrelation. The Variance Inflation Factor (VIF), Breusch-Pagan, and Wooldridge test results (Table 2) suggest these issues are not relevant to our specifications.

4 Results

4.1 The interplay between polycentricity and regional TFP

We structure the discussion of our results around Table 1. Model 1 only includes the exogenous variables HUM, INF, TIN, FDI, and GOV. In Model 2, we add POLY, while Model 3 includes POP and POLY*POP. Models 4-6 provide full model estimates for National URs, Regional URs, and sub-Regional URs, while Model 7 and Model 8 provide results for coastal URs and inland URs. The relatively high R^2 across these models suggests a good fit, with all models explaining at least two-thirds of the variance in TFP across the urban regions.

In Model 1, the coefficients of the variables all have the expected signs and are statistically significant at the 1% level. The signs of the control variables remain consistent across all specifications, albeit with slight differences in size and statistical significance. Overall, the result suggests that an urban region's TFP is above all explained by the level of human capital (HUM), informatization (INF), and foreign direct investment (FDI). This is in line with the findings of other studies (Wang et al., 2019). Meanwhile, the intensities of the tertiary industry (TIN) and government intervention (GOV) have a negative influence on TFP, consistent with the result of Wang et al. (2019). This suggests that governmental control on regional economies has led to productivity loss, possibly because of market distortions (Zhang et al., 2017); the Chinese industrial structure is dominated by 'high-energy consumption, low added value, low marginal cost' (Shen et al., 2020, p. 8), which is not conducive to the improvement of regional TFP.

Turning to the critical variable of our interest, the regression coefficient of POLY is significantly negative: a higher level of polycentricity corresponds to a lower level of TFP. Our first hypothesis (*H1*) is therefore rejected. The results are in line with the significant agglomeration effects of central cities found in Italy and OECD countries (Veneri & Burgalassi, 2012; Brezzi & Veneri, 2015)), while it does not align with the findings of Meijers and Burger (2010) for the United States and Ouwehand et al. (2022) for Europe. We elaborate on this important finding in the discussion.

However, when examining the interaction between polycentricity and size, we find that the interaction term POLY×POP has a significant and positive effect on TFP (Model 3). In other words, there is an impact of polycentricity on TFP that becomes stronger in larger urban regions, which contradicts *H3*. We calculated the population size threshold above which the effect of polycentricity would turn positive. By letting the coefficient of POLY equal zero, it can be estimated that urban regions with a population size of over 20.94 million are more likely to have higher regional TFP when they are more polycentric. Under this criterion, approximately one-third of Chinese urban regions are too small to capture the (alleged) economic benefits of polycentricity fully.

In Models 4-6, the negative impact of polycentricity on productivity is most pronounced in sub-Regional URs, followed by National URs and Regional URs. This suggests that the administrative hierarchy of urban regions leads to differences in POLY's impact on regional TFP. Moreover, there is heterogeneity between coastal and inland regions, with the former being significantly positive and the latter significantly negative (Models 7 and 8). This marked difference suggests that the autonomy granted to local governments is crucial for regional economic growth, potentially because it supports moving towards more dynamic and active cooperation among cities, which has positive externalities for the entire economy. Therefore, our fourth (*H4)* and fifth hypotheses (*H5*) are accepted.

Table 1. Regression result of the baseline model

Variables	Model 1	Model 2	Model 3	Model 4 National URs	Model 5 Regional URs	Model 6 sub-Regional URs	Model 7 Coastal URs	Model 8 Inland URs
Intercept	0.02	-0.07	-0.12	-0.02	-0.76	0.10	3.16	-2.02
	(0.10)	(-0.92)	(0.16)	(-0.04)	(-0.28)	(-0.01)	(0.60)	(-1.72)
POLY		-0.28*	-0.12**	-0.45*	-0.09	-0.61*	0.67*	-0.22*
		(-2.48)	(-2.60)	(-2.18)	(0.20)	(2.34)	(2.01)	(-1.59)
HUM	0.13***	0.11***	0.08***	0.16*	0.10**	0.11	0.02	0.09**
	(3.67)	(3.51)	(3.55)	(1.92)	(1.71)	(2.11)	(0.17)	(3.30)
INF	0.06**	0.05**	0.06**	-0.04	-0.00	0.12*	0.013	0.04
	(2.57)	(2.61)	(2.61)	(-0.79)	(0.02)	(2.55)	(0.24)	(1.24)
TIN	-0.50***	-0.52*	-0.51***	-0.33***	-0.20***	-0.44	-0.47*	-0.52***
	(-5.71)	(-6.13)	(-5.87)	(-2.99)	(-3.93)	(-1.54)	(-2.12)	(-4.93)
FDI	0.01*	0.01*	0.01	0.01*	0.00	0.00	0.00*	0.01*
	(1.61)	(1.28)	(0.01)	(1.56)	(0.01)	(0.10)	(0.01)	(1.86)
GOV	-0.03*	-0.01	-0.04*	-0.04	-0.03	0.07*	-0.12	-0.02
	(1.43)	(-0.99)	(-2.61)	(-0.54)	(-0.04)	(1.54)	(-1.03)	(-0.49)
POP			0.00	0.03	0.08*	-0.01	-0.42	0.21*
			(0.39)	(-0.50)	(1.71)	(-0.23)	(-0.63)	(-0.73)
POLY*POP			0.09**	1.42	0.80**	-0.31	0.34*	0.35**
			(2.06)	(0.94)	(0.36)	(0.21)	(1.61)	(2.75)
R^2	0.65	0.66	0.67	0.91	0.78	0.63	0.67	0.73
Avg.VIF	1.42	1.83	2.03	2.54	2.25	3.72	3.16	2.10
Breusch-Pagan	0.69	0.14	0.00	0.19	0.02	0.10	0.55	0.12
Wooldridge test	0.15	0.19	0.17	0.68	2.15	0.04	0.60	0.00
AIC	-431.61	-449.13	-449.88	-154.52	-201.67	-144.51	-183.97	-487.34
Obs.		228		60	96	72	72	156

$^{***}p< 0.01$, $^{**}p< 0.05$, $^{*}p< 0.1$. t-values are in parentheses

4.2 Exploring the net effects of borrowed size and agglomeration shadow

We now focus on *H2* and explore if and how the effect of POLY on regional TFP can be explained through the relative balance between 'borrowed size' and 'agglomeration shadows.' To this end, we add BOR, ${BOR_{it}}^2$ as well as the interaction item with urban size and with polycentricity into the baseline model. We then re-estimate the regression of sub-samples by differentiating their position in the administrative hierarchies, which allows testing whether more autonomous regions can better exploit the benefits of borrowed size. The results for these regressions are shown in Table 2.

The significant and negative impact of polycentricity on regional TFP re-emerges. Furthermore, according to Model (1), *H2* should be rejected as both BOR and its square term have no apparent effect on regional TFP. This observation can be interpreted in two ways: (1) neither borrowed size nor agglomeration shadow effects occur, or (2) borrowed size and agglomeration shadow effects even each other out.

However, a different pattern emerges when introducing BOR*POP in Model (2). Our results suggest that the net effects of borrowed size appear when urban size reaches a certain threshold. In other words: in larger urban regions, cities seem to benefit from borrowed size effects (positive spillovers), while this is less likely to happen in smaller urban regions (the effect turns positive when the population size of urban regions exceeds 18.3 million). And finally, when introducing BOR*POLY (Model (3)), we find no statistically significant outcome.

However, the results for the subsamples (Model (4) to (6)) do not replicate the patterns of the full samples, and there are even sizable differences between them. For National URs, the coefficients of BOR and ${BOR_{it}}^2$ are positive and negative, respectively, implying that the productivity increases with borrowed size. Still, it occurs only when the borrowed size effect is relatively large. For Regional URs, the empirical results also reveal a negative *nonlinear* relationship, albeit in a different direction – productivity firstly increases and then decreases with borrowed size. Finally, the (direct) borrowed size effect is significantly negative for sub-Regional URs. Together these results imply that the negative externalities from inter-city interaction (i.e., agglomeration shadows) could be mitigated by a more decentralized system in more autonomous URs, plausibly through more voluntary coordination among small and large cities.

Table 2. Regression result of the net effect benefits of borrowed size and agglomeration shadow

Variables	Model (1)	Model (2)	Model (3)	Model (4) National URs	Model (5) Regional URs	Model (6) sub-Regional URs
Intercept	-1.08(-1.62)	-0.55(-0.71)	-1.01* (-1.51)	-5.63*(-1.92)	2.28(1.68)	-1.74(-1.29)
POLY	-0.25**(-2.09)	-0.27** (2.78)	-0.21*(-1.67)	0.09*(-2.60)	0.25(1.30)	-1.11**(-2.85)-
HUM	0.10**(2.56)	0.09*** (2.78)	0.10***(3.28)	0.00(-0.02)	0.02(0.22)	0.12**(2.24)
INF	0.06**(-6.20)	0.05**(2.27)	0.06**(2.70)	-0.01(-0.31)	-0.01(-0.14)	0.12**(2.46)
TIN	-0.55***(-6.20)	-0.53 *(-5.96)	-0.55***(-6.26)	-0.30**(-2.49)	-0.52***(-3.93)	-0.57*(-1.96)
FDI	0.01(1.34)	0.01*(1.59)	0.01*(1.50)	0.01(0.88)	0.01(0.73)	0.00(-0.19)
GOV	-0.03(-0.78)	-0.04(-1.06)	-0.04(-1.03)	0.00(0.06)	-0.06(-0.78)	-0.14(-1.29)
POP	0.01(0.19)	0.09(0.16)	0.01(0.26)	-0.02(-0.33)	0.07*(1.57)	-002(-0.26)
BOR	0.96(1.14)	0.01(0.01)	0.83(0.98)	6.85*(1.97)	-4.20**(-2.15)	2.65*(1.62)
BOR^2	-0.18(-0.59)	-0.15(0.39)	-0.12(0.98)	-2.36*(-1.99)	1.33**(2.04)	-0.75(-1.20)
BOR*POP		0.29*(1.45)				
BOR*POLY			-0.46(-1.13)	4.67**(2.25)	-0.20(-0.25)	-0.26(-0.30)
R^2	0.67	0.67	0.67	0.91	0.79	0.64
Avg.VIF	11.81	10.97	10.85	11.34	10.92	12.49
Breusch-Pagan	0.55	0.45	0.60	0.40	0.26	0.89
Wooldridge test	0.52	0.49	0.48	0.12	0.33	0.34
AIC	-671.77	-682.14	-671.32	-247.67	-304.78	-157.72
Obs.		228		60	96	72

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. t-values are in parentheses.

4.3 Dealing with endogeneity

To ensure that the direction of causality runs from polycentricity to economic performance, we employ a fixed effect (FE)-instrument variable (IV) model. The robustness test results (Appendix F) indicate that the IVs are practical: they are correlated with POLY but not with TFP. When using the IVs estimates to assess the impact of POLY on TFP, the results confirm our main finding from the baseline model: a higher level of polycentricity correlates with lower total factor productivity. More importantly, the endogeneity test results suggest that endogeneity is not a concern in our specifications (for a detailed overview of the regression results, see Appendix F).

5. Discussion and conclusions

Urban centres in PURs are often hypothesized to 'share' agglomeration economies, as cities can borrow size from nearby cities to enjoy productivity gains linked to scale. While a growing body of research is developing explanations for these dynamics, findings remain inconclusive regarding where, to what extent, and under which conditions these effects occur. One possible factor explaining the inconsistency in results pertains to the variety of measurement schemes invoked to capture both polycentricity (Caset et al., 2022) and economic productivity (Ouwehand et al., 2022), with ongoing efforts in both domains to arrive at more conceptual sound and analytically accurate measures.

Against this background, our paper contributes to the part of the literature systematically investigating the alleged economic advantages of polycentric urban development. Focusing on the case of UR's in China, our methodology builds explicitly on and combines elements of recent studies that have pushed the debate forward: Derudder et al. (2021), who reviewed the different choices when measuring polycentric urban development, Ouwehand et al. (2022), who proposed using TFP as a more accurate measure of productivity; Wang et al. (2019), who analyzed the economic performance of Chinese PURs using cross-sectional data; and Harari (2020), who constructed instrumental variables for urban shapes based on geographical obstacles encountered by expanding cities. We developed a longitudinal research design that assesses endogeneity effects to enhance the robustness of the results.

The major empirical results can be summarized into five main findings:

(1) *Chinese urban regions that are more polycentric exhibit lower total factor productivity*

(2) *Polycentricity nonetheless starts positively impacting regional TFP when population size increases*

(3) *Cities can borrow size from nearby cities when the size of urban regions is large, thus contributing to regional economic growth*

(4) *The negative impact of polycentricity on regional TFP is more significant in urban regions that are lower in the administrative hierarchy*

(5) *Urban regions in coastal China exhibit marked differences regarding the influence of polycentricity on regional TFP compared to those in inland China.*

In general, these results indicate that agglomeration economies, proxied by TFP, are relatively less present in Chinese urban regions that are more polycentric. While we shared the geographical scope of Wang et al. (2019) and adopted a similar approach to measuring polycentricity, we arrived at opposite findings. This may be related to how these authors measured economic productivity (LP instead of TFP), suggesting that different types of urban advantages may have developed differently in PURs. More specifically, the kinds of agglomeration externalities, mainly those spurring technology, organizing innovation, and promoting management skills, are associated with the leading role of central cities. In contrast, others are related to the scale of the labour market and may cover a larger area. This may be explained by the observation that intangible factors in a production process require a large agglomeration that provides the basis to share, match, and learn (Duranton et al., 2004) between individual cities or firms. In contrast, the tangible production factors face more competition within a single large agglomeration, causing economic activities to locate in cities with lower capital and labour costs. Although these ideas require further examination, we believe they provide valuable clues to understand better why polycentric URs may perform better in terms of LP than TFP in China.

We expected polycentricity to perform better in small urban regions but arrived at the opposite findings. In our view, the difference with the results of Meijers and Burger (2010) and Ouwehand et al. (2022) can be related to a fundamental conceptual question that is rarely discussed in the literature: at what scale do we expect urban polycentricity to matter? Some researchers argue that cities are less functionally related in large PURs (Meijers & Burger, 2010), which might explain the attenuation of benefits of polycentricity with urban size. To some extent, this may be true in the US and Europe, where many inter-city movements occur via well-developed infrastructure networks. However, this assumption arguably applies less to urban regions in China, where both the territorial scale and the total population of 'urban regions' are significantly higher. For example, the median travel distance between cities in the YRD is approximately five times larger than that of the Randstad and the San Francisco Bay Area (Appendix G). In other words, we cannot expect the knowledge-related advantages that may derive from large central cities (such as Shanghai) to easily spread to the entire YRD region compared to PURs in Europe and the US.

The importance of contextualizing empirical findings across (inter)national borders/geographical borders also pertains to the particular institutional-economic context in China. Our results indicate that polycentricity negatively influences regional productivity, particularly in PURs planned and developed through a strong top-down design. This can be traced back to a system where polycentric spatial patterns are created for the sake of the collective (regional) interest. Although the local governments must comply with the centrally initiated plans, they would selectively follow to prioritize their own interests. In fact, the scope of inter-city cooperation remains limited mainly to transport infrastructure sharing (Li & Wu, 2018). Without more bottom-up collaboration between cities, a deliberate polycentric population distribution may cause efficiency losses due to the lack of regional markets, cross-jurisdictional mobility, and other factors essential for regional economic development. This raises an important policy question: with diverse motivations from different stakeholders mixed in processes of region-building, regional economic growth may not be easily achieved by 'imaginary' spatial configurations.

In general, our analysis did *not* produce evidence that polycentric urban development is linked with higher regional economic productivity in China. As a result, we believe this calls for more judiciousness in policy and planning aspirations toward hoped-for regional-economic benefits. Although the meaning of the population threshold above which urban regions benefit from polycentricity is limited, it suggests that it is short-sighted to plan for polycentric patterns across all urban regions universally. For the largest urban regions, such as the Yangtze River Delta and the Pearl River Delta, local governments should consider measures to promote inter-city connectivity to secure the net benefits of 'borrowed size,' e.g., building integrated social security networks to facilitate labour mobility. For smaller urban regions, such as the Ningxia-Yellow River and Central Shanxi, the agglomeration economies of central cities have not been fully exerted, and pursuing multi-centre development will lead to the loss of productivity rather than enhance it. This suggests that the moderate gap between the city sizes should be maintained to avoid excessive polycentricity, which may hamper the leading effects of the central cities on their surroundings.

Our last point concerns the analytical framework adopted in this study. We used an integrated indicator to capture the net benefits of population spillovers between neighbouring cities. In so doing, two opposite effects – borrowed size and agglomeration shadows – are collapsed into a single term, making it difficult to assess their individual effects. However, the proxy we adopted here suffices because we are mainly interested in the overall benefits passed onto the economy as a whole. In research where it becomes crucial to distinguish between the benefits/disadvantages of being connected in regional urban networks, an operational refinement should be included in line with Meijers and Burger (2017) and Volgmann and Rusche (2020). Moreover, we proxied the effect by seeing it as a function of population and distance to neighbouring cities, as this captures the potential to 'generate wide demand for goods and a pooled labour supply' (Camagni et al., 2017, p. 255). Different types of data would have been more appropriate if we had focused on other aspects of borrowed size effects, such as the presence of high-level functions in neighbouring cities.

Our findings call for further research in several directions. First, we found that the different specifications of economic efficiency affect the relationship between polycentricity and regional economic performance. This calls for a closer inspection of the sensitivity of the impact on the choice of economic measures. Second, TFP has only recently been adopted to analyze the economic performance of spatial structures, and the knowledge base is, therefore, still relatively limited. Future research could explore its suitability by diversifying the empirical contexts, enlarging the longitudinal data frame, and refining it using sectoral data. Third, future research could adopt a functional lens to identify polycentric spatial structures, which may align better with some of the key constructs in the theoretical framework (e.g., TFP capturing knowledge spill-overs may largely depend on the nature and strength of inter-city relations). Fourth, separating the effects of borrowed size and agglomeration shadows would result in a more refined understanding of both forces. And finally, we only focused on the regional scale, as it is the territorial scale at which PUR policy initiatives in China operate. A multiscalar perspective may provide more insight (Wang et al., 2019, p. 1638). Integrating analyses at different scales into a unified framework may allow us to better understand the dynamics of the productivity-spatial structure-polycentricity interactions and choose the appropriate scale for policy intervention.

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