

Regional polycentric spatial patterns and air pollution—An empirical study of German metropolitan regions

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Introduction

A polycentric urban region (PUR)

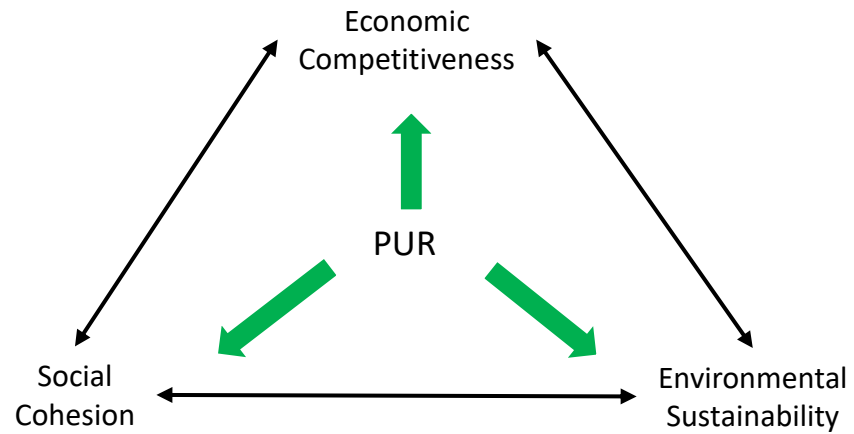
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- each center retains unique economic and social role yet benefit from shared infrastructure.

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Spatial policy in EU (ESDP, 1999; EU Urban Agenda, 2016):

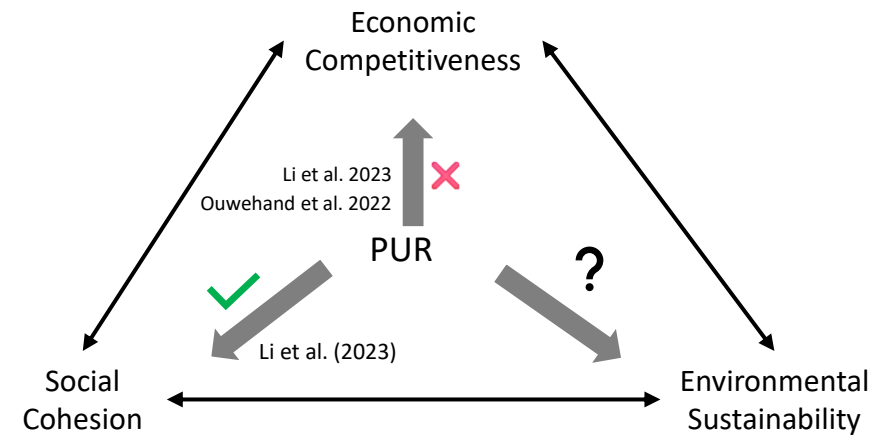
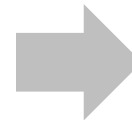
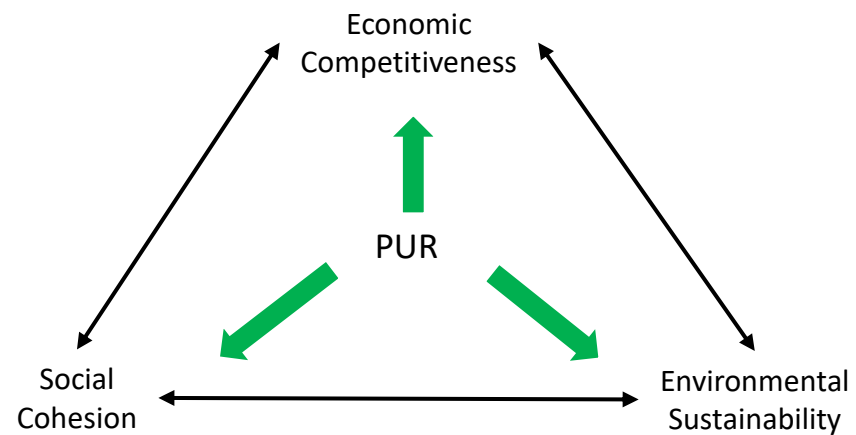


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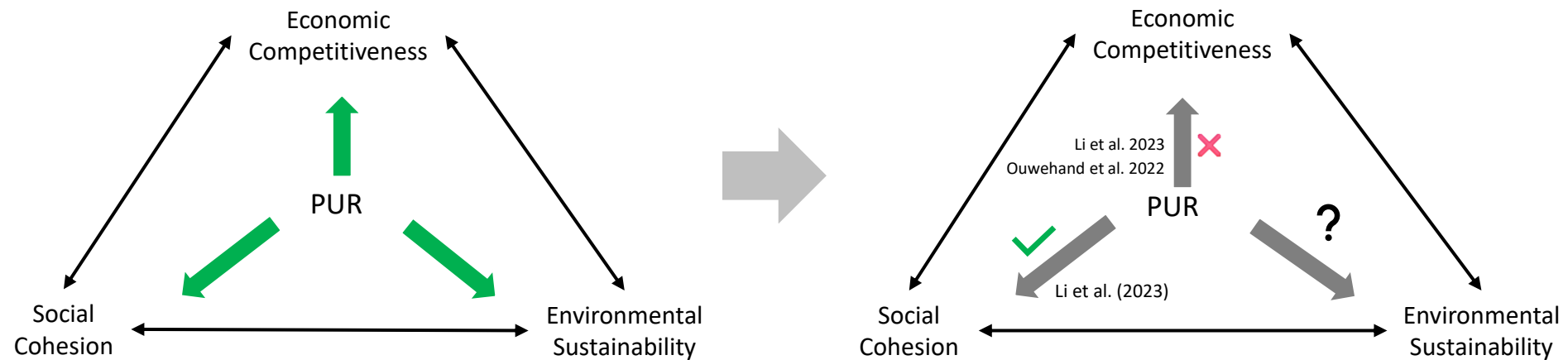


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Research objectives:

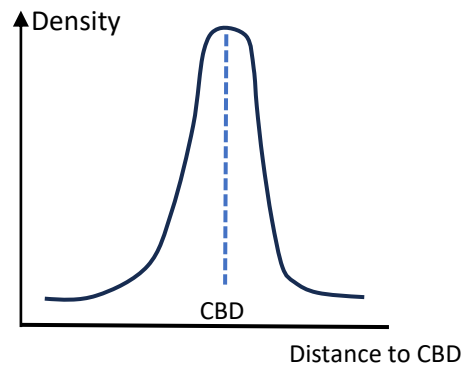
- To examine the supposed environmental impacts— the relationship between polycentricity and ambient air quality in German metropolitan regions.
- To Investigate the mechanisms leading to our findings—the differences in region size, density, and commuting patterns between monocentric and polycentric regions, and their impacts on air quality.

Debate

A dilemma in regional and spatial planning policy

- **Denser and compact** pattern—concentrated economic activity → greater pollution exposure (Ahlfeldt & Pietrostefani, 2019; Schweitzer & Zhou, 2010)

Compact & monocentric pattern

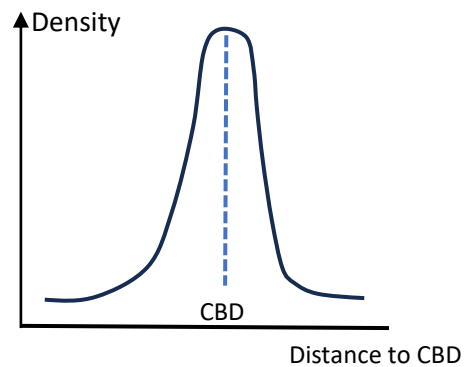


Debate

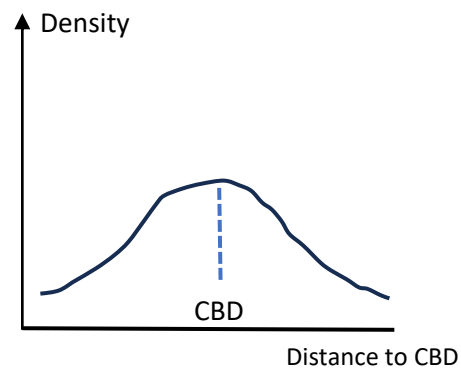
A dilemma in regional and spatial planning policy

- **Denser and compact** pattern—concentrated economic activity → greater emissions and pollution exposure (Ahlfeldt & Pietrostefani, 2019; Schweitzer & Zhou, 2010)
- **low-density and sprawling** pattern—more vehicular trips, vehicle mileage traveled → higher ambient air pollution concentrations (Bereitschaft & Debbage, 2013; Stone, 2008)

Compact & monocentric pattern



Sprawling and decentralized pattern

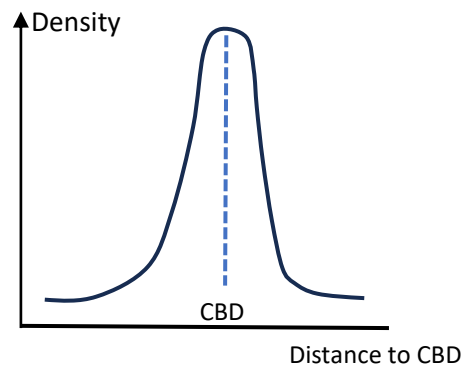


Debate

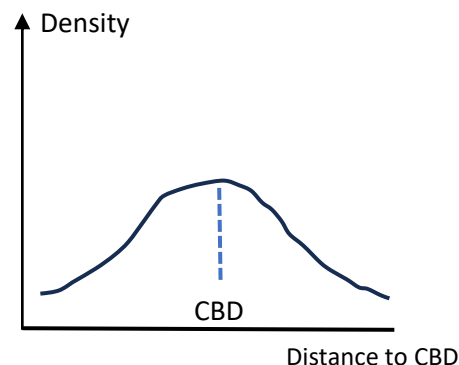
A dilemma in regional and spatial planning policy

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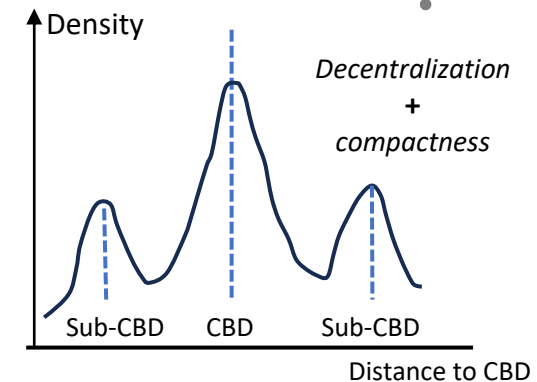
Compact & monocentric pattern



Sprawling and decentralized pattern



Polycentric pattern ?



Can Polycentricity reconcile this dilemma (dichotomy)?

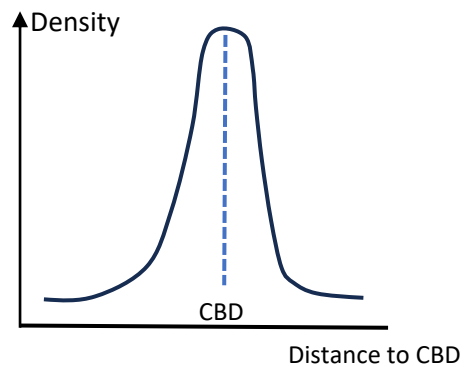
- integrate the features of both *compact* and *decentralized* developments

Debate

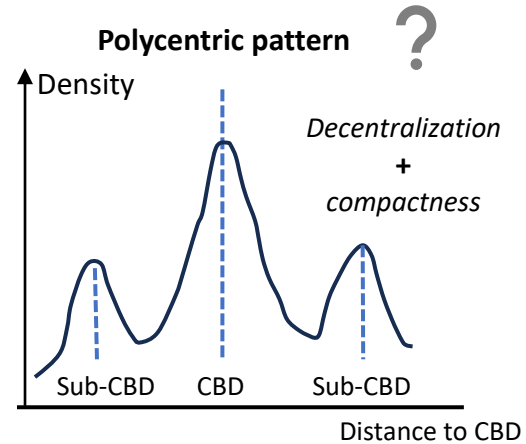
Proponents' view:

- Density:
 - ✓ lower density than monocentric setting → lowering pollutant concentration levels;

Compact & monocentric pattern



Polycentric pattern

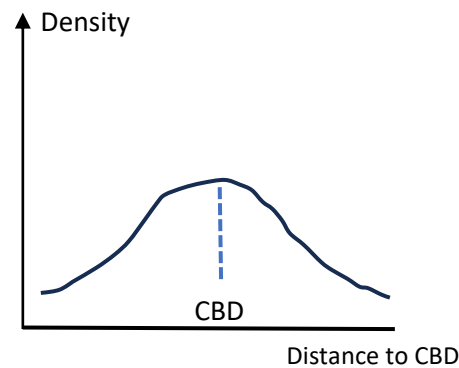


Debate

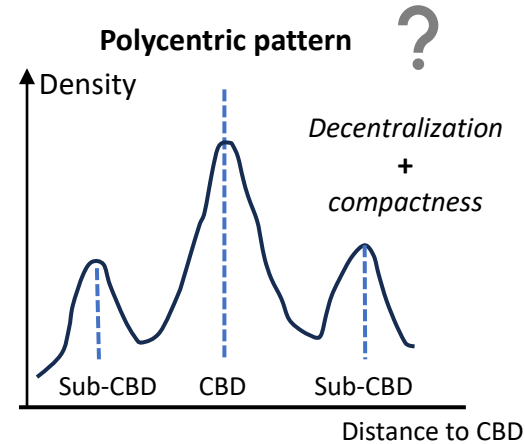
Proponents' view:

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 - ✓ lower density than monocentric setting → lowering pollutant concentration levels;
 - ✓ higher density than sprawling setting → mitigating pollution from energy consumption and traffic associated with urban sprawl.

Sprawling and decentralized pattern



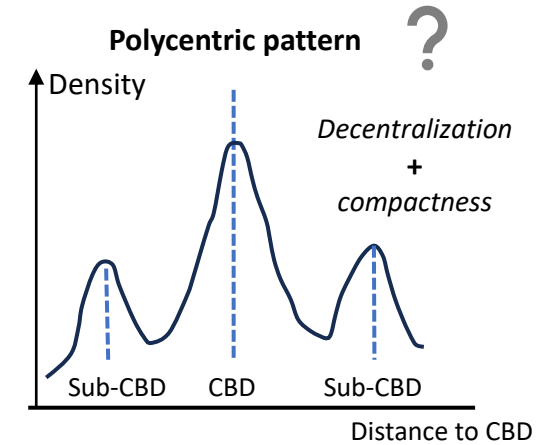
Polycentric pattern



Debate

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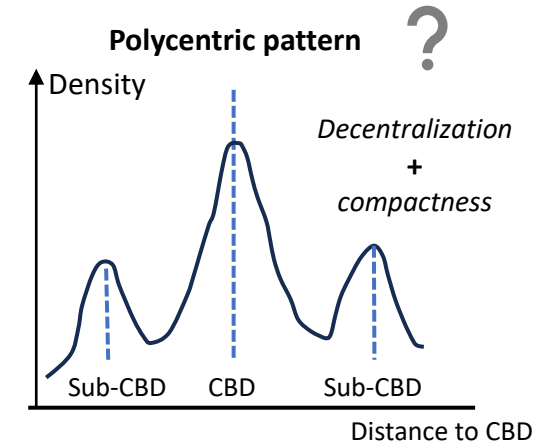
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- Commuting pattern:
 - ✓ fostering co-location of residences and workplaces



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Opponents' view—Polycentrism may

- ✓ simultaneously contribute to urban sprawl and the associated negative externalities.
- ✓ lead to substantial inter-municipality commuting trips due to intensive functional links.
- ✓ fail to create walkable built environment or reach the sufficient scale necessary for public transit services.

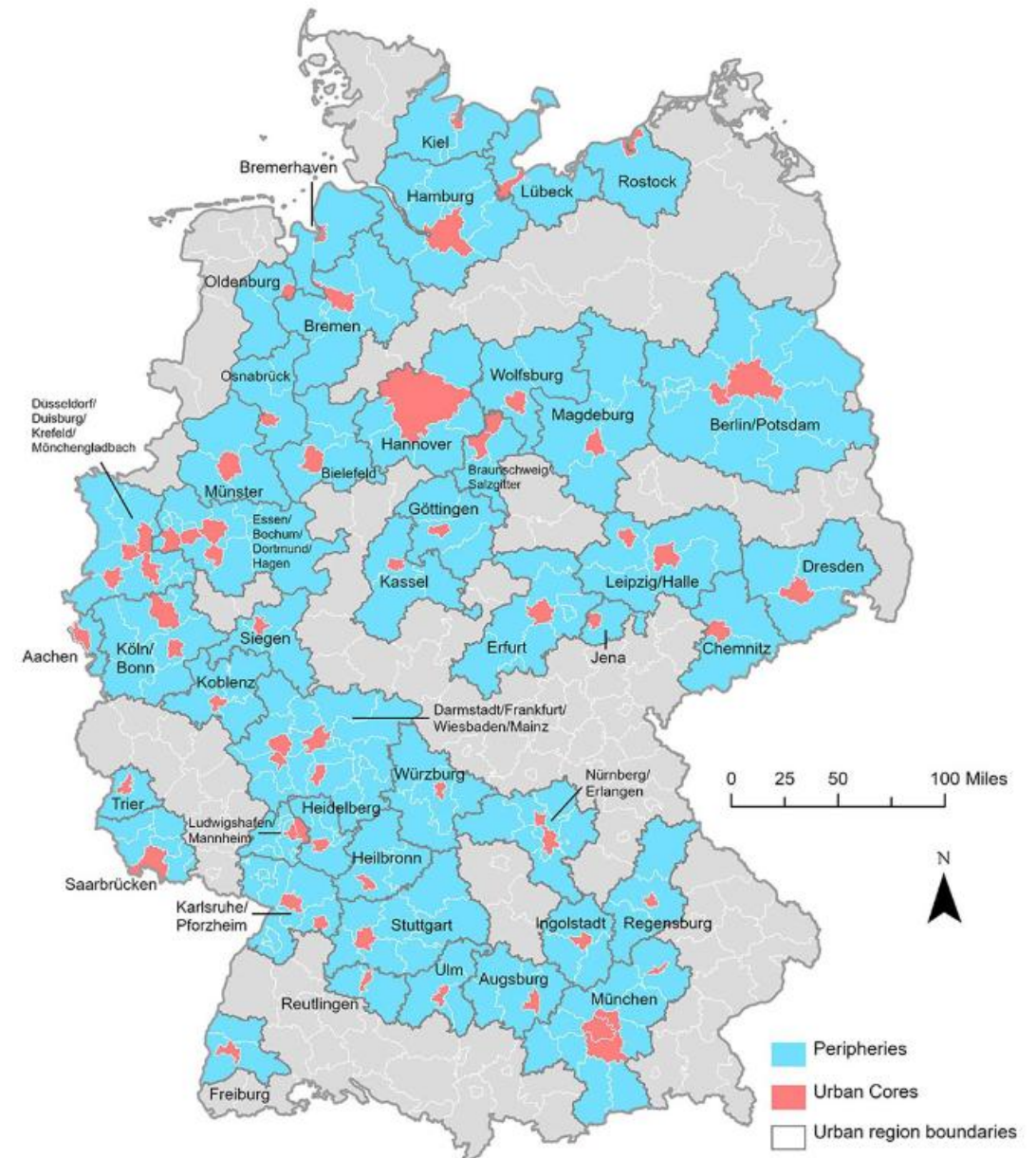
Data and Methods—Study regions and datasets

German urban regions (*Großstadtregionen*)

- **Urban core(s)**—regional center city; population > 100,000
- **Hinterlands**—strong commuting relationships with cores
- 50 regions

Datasets

- Satellite-derived PM_{2.5} (van Donkelaar et al. 2021)
- Socio-economic datasets: INKAR data platform (BBSR)
- Commuting flow: the Federal Employment Agency



Data and Methods— Measures of polycentricity

1. Morphological polycentricity:

$$P_i(n) = 1 - \sigma_n / \sigma_{\max} \quad (n = 2, 3, 4)$$

σ_n : std.dev of **employment** distribution among municipalities

2. Rank-size distribution:

$$\ln(Rank) = \alpha + \beta \ln(size)$$

Size: **employment** of a municipality,

Rank: the rank of employment within an urban region

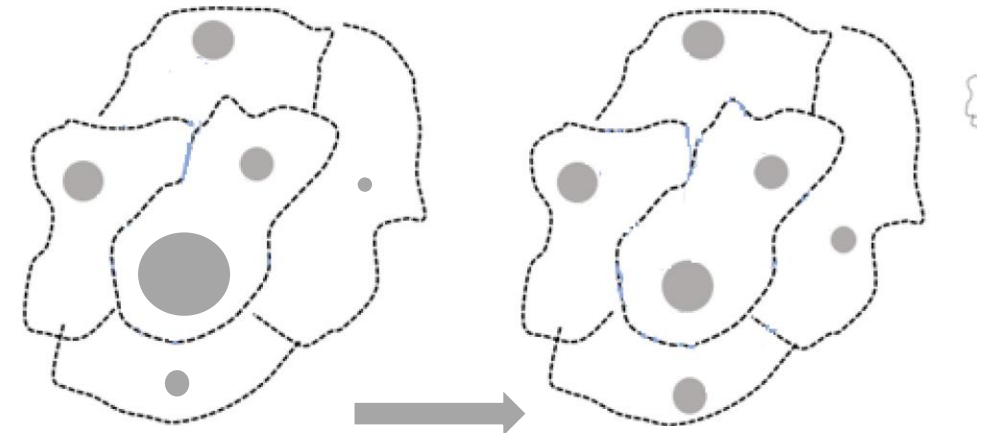
3. Functional polycentricity:

$$P_F(n) = (1 - \sigma_f / \sigma_{f\max}) * \Delta$$

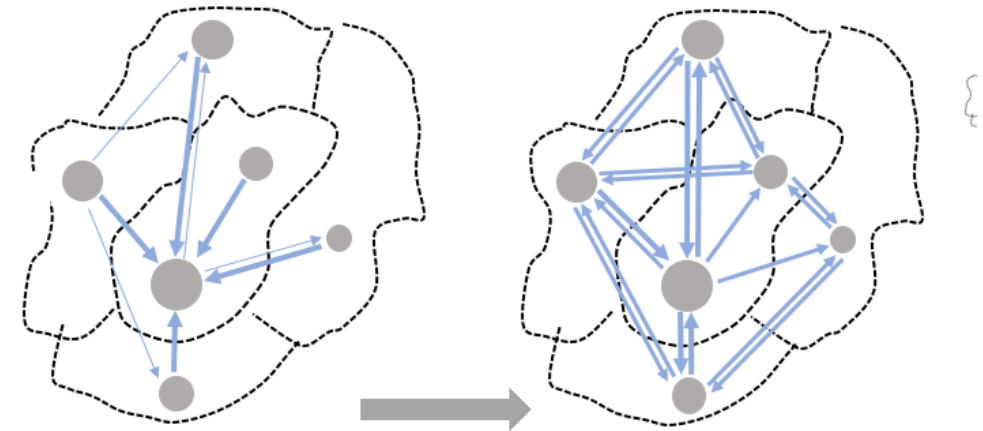
σ_f : std.dev of **commuting flows** among municipalities

$\sigma_{f,\max}$: std.dev of benchmark monocentric region;

Δ : density of the network

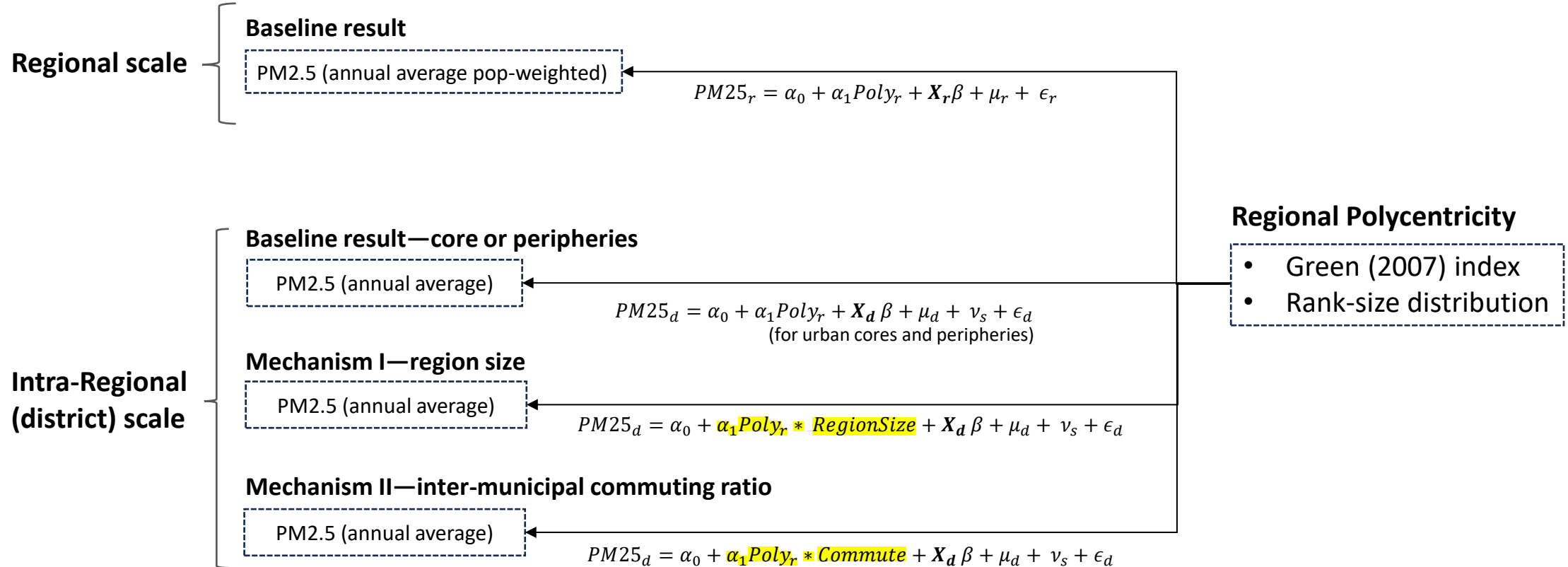


Higher level of morphological polycentricity



Higher level of functional polycentricity

Data and Methods—Empirical Strategy



Analysis—baseline results

Regional-scale:

- higher degree of polycentricity **does not** contribute to reduced air pollution across regions

Intra-regional scale—being situated in a more polycentric context:

- For **urban cores** (Model 2), polycentricity **worsens** air quality
- For **peripheries** (Model 3): polycentricity **does not** impact air quality

Table 2: Regressions to test the impacts of polycentricity on air pollution at both regional and intra-regional scale.

Variables (in logarithmic form)	Regional scale	Intra-regional scale	
	(1) All regions	(2) UrbanCore	(3) Periphery
Poly	-.0288 (.0284)	.0498* (.0249)	.009 (.0148)
Population density	.1927** (.0904)	.094* (.0476)	.0543** (.0244)
Ratio of Greenspace	-.0001 (.0257)		
Mean temperature (annual)	.9294* (.5105)	.244 (.1889)	.4523*** (.1127)
Mean precipitation (annual)	-.4132*** (.1432)	-.0878 (.0958)	-.0941** (.0438)
GDP per capita	.0717 (.0479)	.0054 (.0284)	-.0288 (.0184)
Tertiary employment	-.0359 (.1072)	-.125** (.0574)	-.0093 (.0459)
Unemployment	.0281 (.0549)	.0145 (.0301)	.0059 (.0252)
UrbanCore			
Region fixed effects	Y	Y	Y
State fixed effects		Y	Y
Constant	7.7395*** (2.7447)	1.6057 (1.2627)	.6967 (.6676)
Observations	50	58	188
R-squared	.5412	.82	.7044

Notes: a). the variable (ROG), ratio of urban green spaces is missing for all models at the intra-regional scale. b). All modes include Region and State fixed effects to account for unobserved, location-specific factors that may influence air pollution. c). The Regional-scale model (1) presents robust standard errors in parentheses. The intra-regional models (2), (3), (4), and (5) use clustered robust standard errors. Observations are clustered at the regional level.

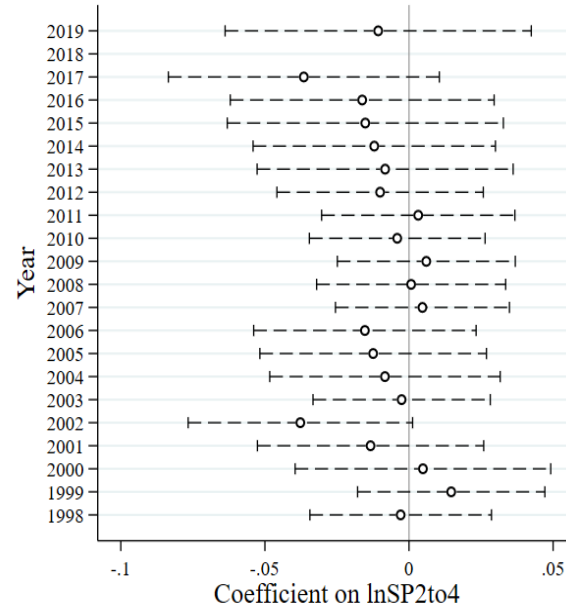
*** $p < .01$, ** $p < .05$, * $p < .1$

Analysis—baseline results extension (1998-2019) and Robustness

regional scale analysis

All Districts

Coefficients and 95% CI for lnSP2to4



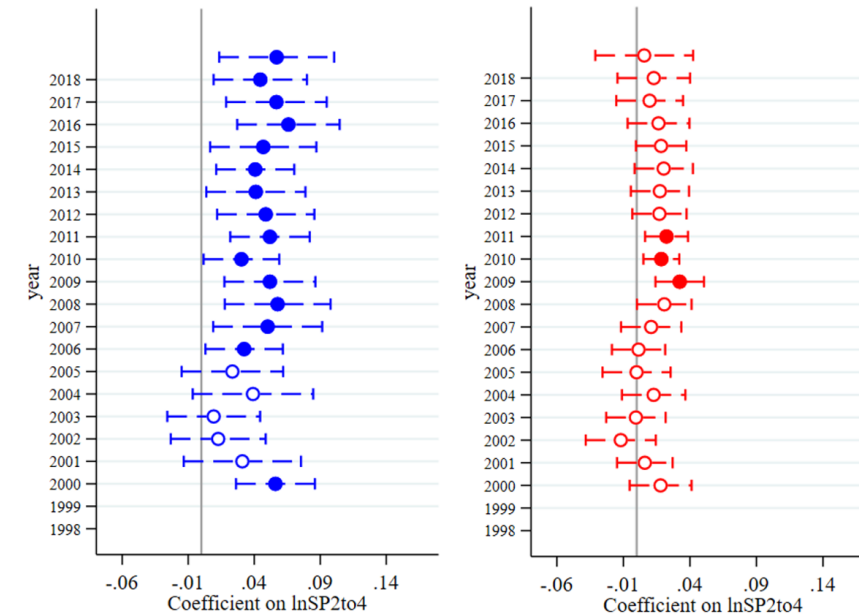
Intra-regional scale analysis

Urban Cores

Peripheries

Coefficients and 95% CI (core)

Coefficients and 95% CI (non-core)



Solid circles represent *statistically significant* results, while **hollow circles** indicate results are *not statistically significant*.

Mechanism analysis I – population density and region size

Conclusion:

- **Urban cores** in large- and medium-sized polycentric regions experience higher air pollution
- **Peripheries** in large polycentric regions experience higher air pollution.
- Air pollution generated by polycentricity is amplified in large cities

Table 3: Intra-regional analysis regarding the moderating effects of population density on air pollution.

Variables (in logarithmic form)	(1) UrbanCore	(2) Periphery
Poly (benchmark: small)	-.0444 (.0514)	-.0391 (.0274)
Poly × Medium-size region	.1175* (.062)	.0602 (.0389)
Poly × Large-size region	.1169** (.0483)	.0633** (.0294)
Medium-sized region	.146* (.0834)	.0644 (.0429)
Large-sized region	.17** (.0712)	.1084*** (.0339)
Control variables	Y	Y
Region fixed effects	Y	Y
State fixed effects	Y	Y
Constant	2.2368 (1.3481)	1.274 (.7932)
Observations	59	194
R-squared	.8622	.7406

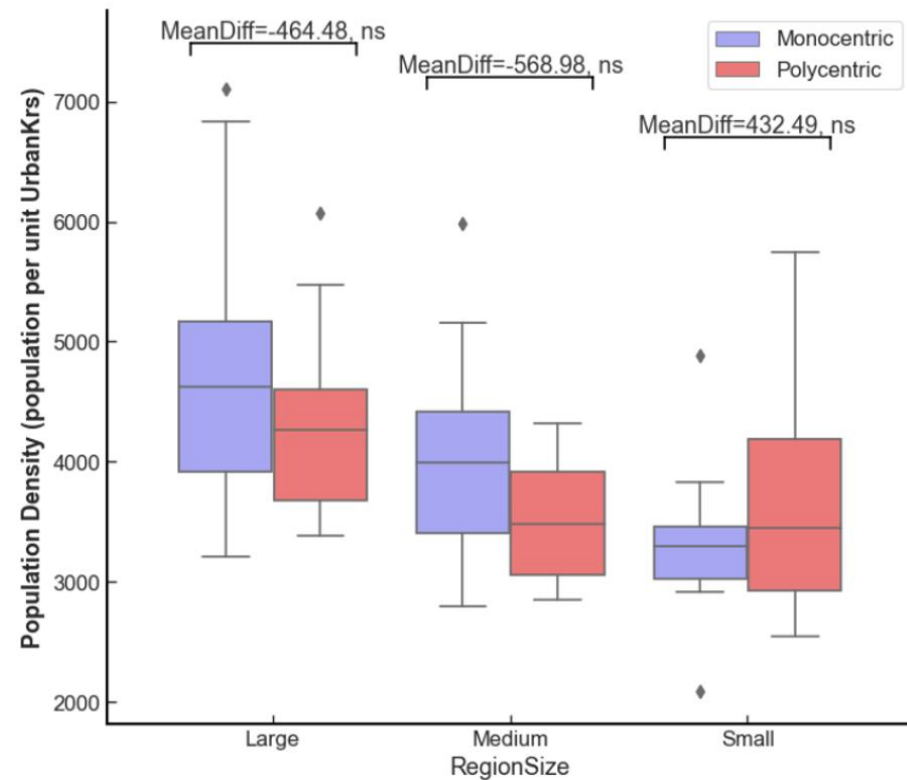
Note: a). All regression models include a set of control variables including population density, total population, GDP per capita, employment in tertiary industry, unemployment rate, mean temperature (annual), and mean precipitation (annual). b). All modes include Region and State fixed effects to account for unobserved, location-specific factors that may influence air pollution.

Clustered-Robust Standard errors are in parentheses. Observations are clustered at the regional level.

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Mechanism analysis I – population density and region size

b Urban core(s)

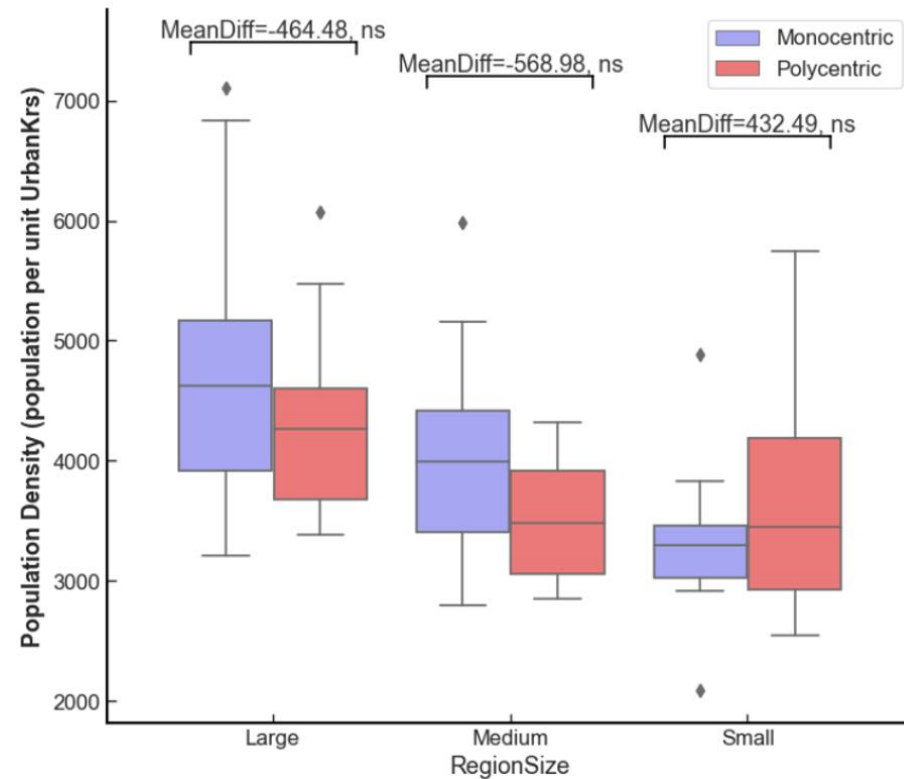


b: Comparison of Density in **Urban Cores** across monocentric and polycentric regions by region size

- no significant differences in density

Mechanism analysis I – population density and region size

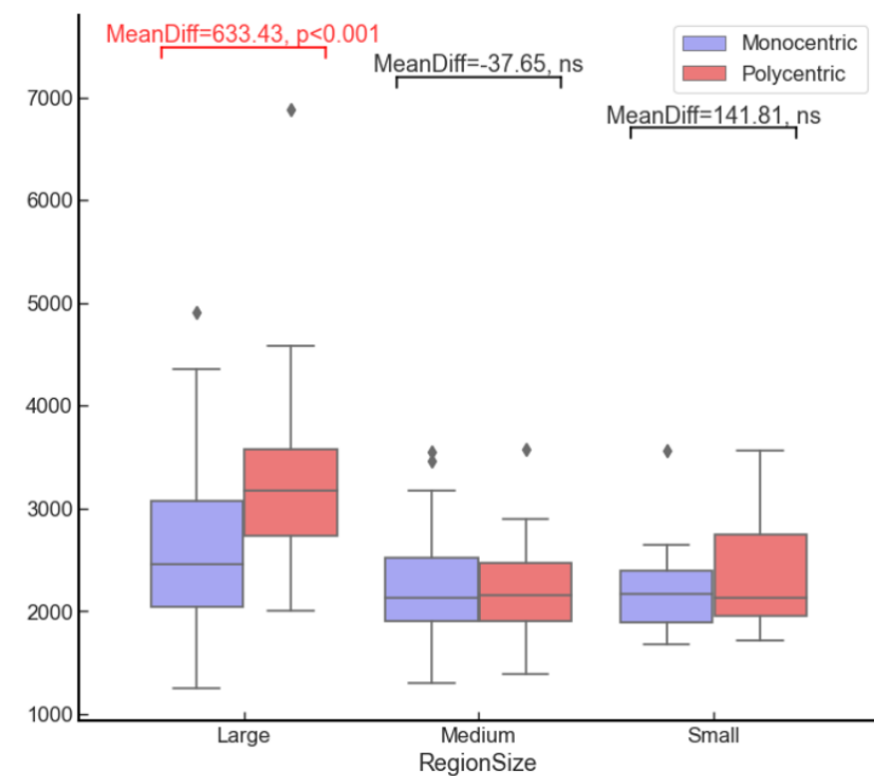
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c Peripheries

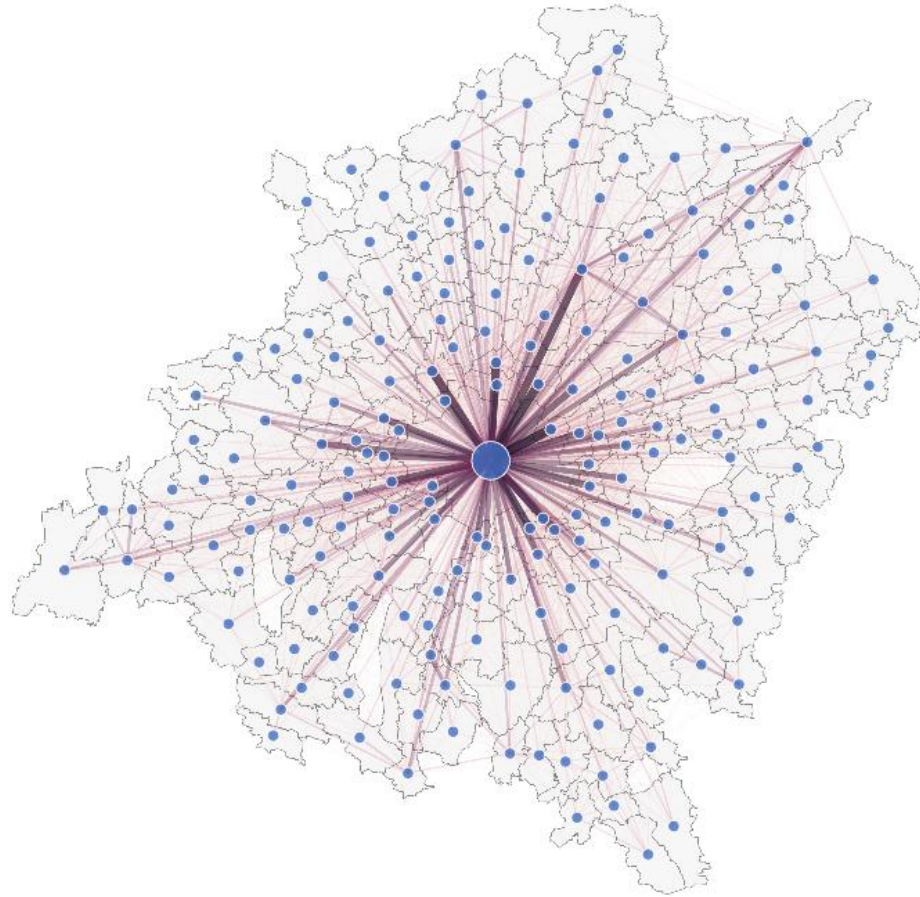


c: Comparison of Density in **Peripheries** across monocentric and polycentric regions in terms of region sizes

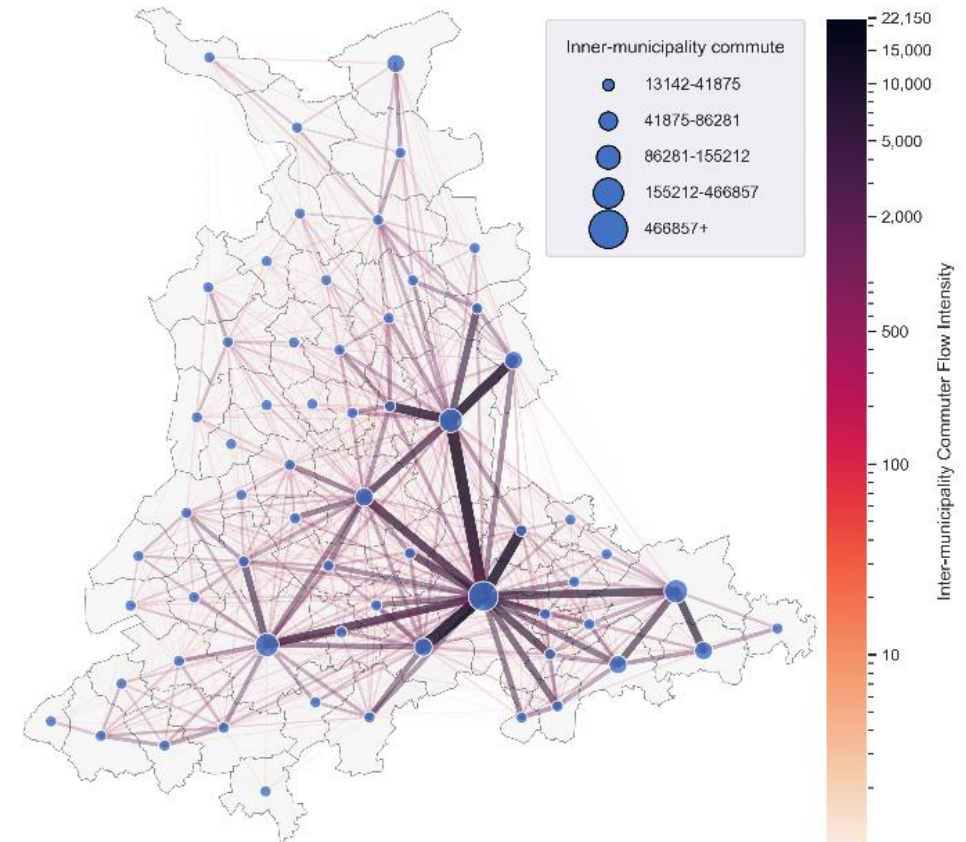
- In large regions, spillovers from urban core(s) trickle down to peripheries

Mechanism analysis II – commuting patterns

Munich Region



Düsseldorf-Duisburg-Krefeld-Mönchengladbach Region



Mechanism analysis II – commuting patterns

Model (1): a higher proportion of inter-municipal trips contributes to increased local pollution

Model (2)—moderating effect: the influence of commute on air pollution increases as regions transition from monocentric to polycentric.

Model (3): the moderating effect is greater for urban core(s) than for peripheral districts in a polycentric region.

Model (4): the moderating effect is greater for medium- and large-sized regions than for small regions.

Table 4: Intra-regional analysis regarding the moderating effects of Urban core/peripheries and region size on air pollution.

Variables (in logarithmic form)	(1)	(2)	(3)	(4)
	All Districts Commute	All Districts Poly×Commute	All Districts Poly×Commute ×UrbanCore	All Districts Poly×Commute ×Size
Poly	.0132 (.0147)	.0726* (.0362)	.0302 (.0462)	-.2013*** (.0506)
Commute	.0579*** (.0215)	.1278*** (.0343)	.0857* (.0452)	-.0753 (.052)
Poly×Commute		.0503* (.0252)	.0174 (.0326)	-.1178*** (.0381)
UrbanCore×Poly×Commute			.0645* (.0333)	
Medium×Poly×Commute				.1578*** (.0494)
Large×Poly×Commute				.1817*** (.048)
UrbanCore			.081 (.0577)	
Medium-size region				.2797*** (.079)
Large-size region				.4256*** (.0769)
Control Variables	Y	Y	Y	Y
Region fixed effects	Y	Y	Y	Y
State fixed effects	Y	Y	Y	Y
Constant	1.8452*** (.6237)	2.0537*** (.5444)	1.9539*** (.4969)	2.6922*** (.7271)
Observations	246	246	253	253
R-squared	.7271	.7341	.74	.7835

Notes: a). To ensure the clarity and readability of this table, we have removed some interaction terms that are not relevant to the conclusions, including UrbanCore×Poly and UrbanCore×Commute in Model (3); Medium×Poly, Large×Poly, Medium×Commute, and Large×Commute in Models (4), (5), and (6). The complete regression table, including all variables, can be found in the supplemental materials. b). All regression models include a set of control variables including population density, total population, GDP per capita, employment in tertiary industry, unemployment rate, mean temperature (annual), and mean precipitation (annual).

Clustered-Robust Standard errors are in parentheses. Observations are clustered at the regional level.

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Conclusions and policy implications

Findings:

- Regional-scale analysis—polycentrism has no significant effects in reducing air pollution.
- Intra-regional analysis—positioning in a more polycentric region
 - urban cores ↑ pollution level; peripheral districts ✗ no effects...
 - larger PURs ↑ pollution level.

Explanation:

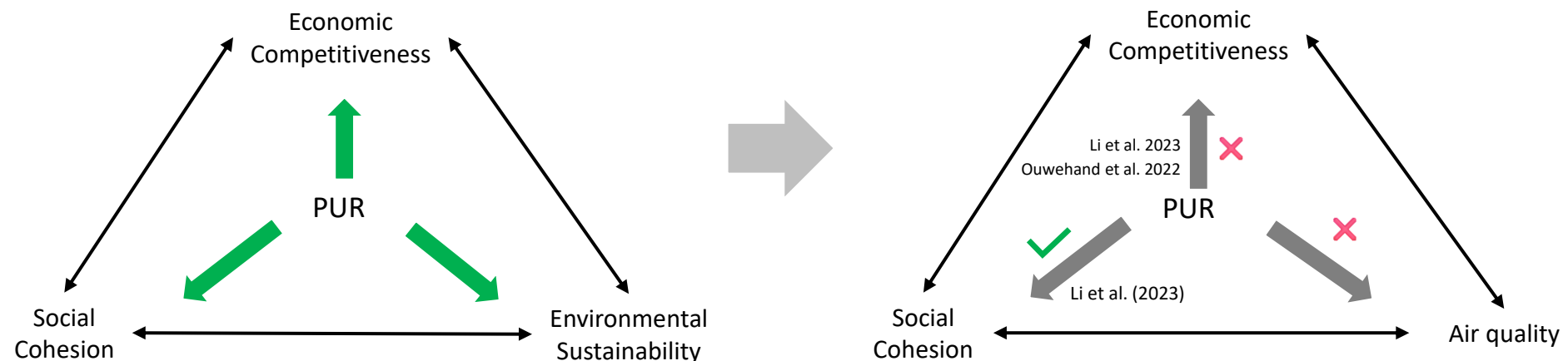
- Population density—spillovers from urban cores benefit nearby peripheries, leading to higher density and, consequently, higher air pollution concentration. This effect is only significant in large regions.
- Inter-municipal commuting ratio—transitioning to a polycentric structure amplifies the effect of commute on air pollution. This effect is more pronounced in larger regions.

Conclusion:

- A PUR is not efficient and sustainable to accommodate larger and high-density urban development.
- A PUR generates more traffic related air pollution.
 - Co-location of residence and workplace? No!
 - A PUR stimulates longer distance and higher level of congestion contribute by the intensive functional links among multiple centers within the same region.

Conclusions and policy implications

- The presence of multiple centers of equivalent size
 - a relatively lower population density—undermines the establishment of public transit system.
 - in turn, leads to increased reliance on private vehicles.
 - polycentric development exacerbates the job-housing imbalance
- We do not recommend German regions to pursue polycentrism based on its performance in mitigating pollution.
- A polycentric pattern is not a one-size-fit-all solution to resolve all spatial and regional issues



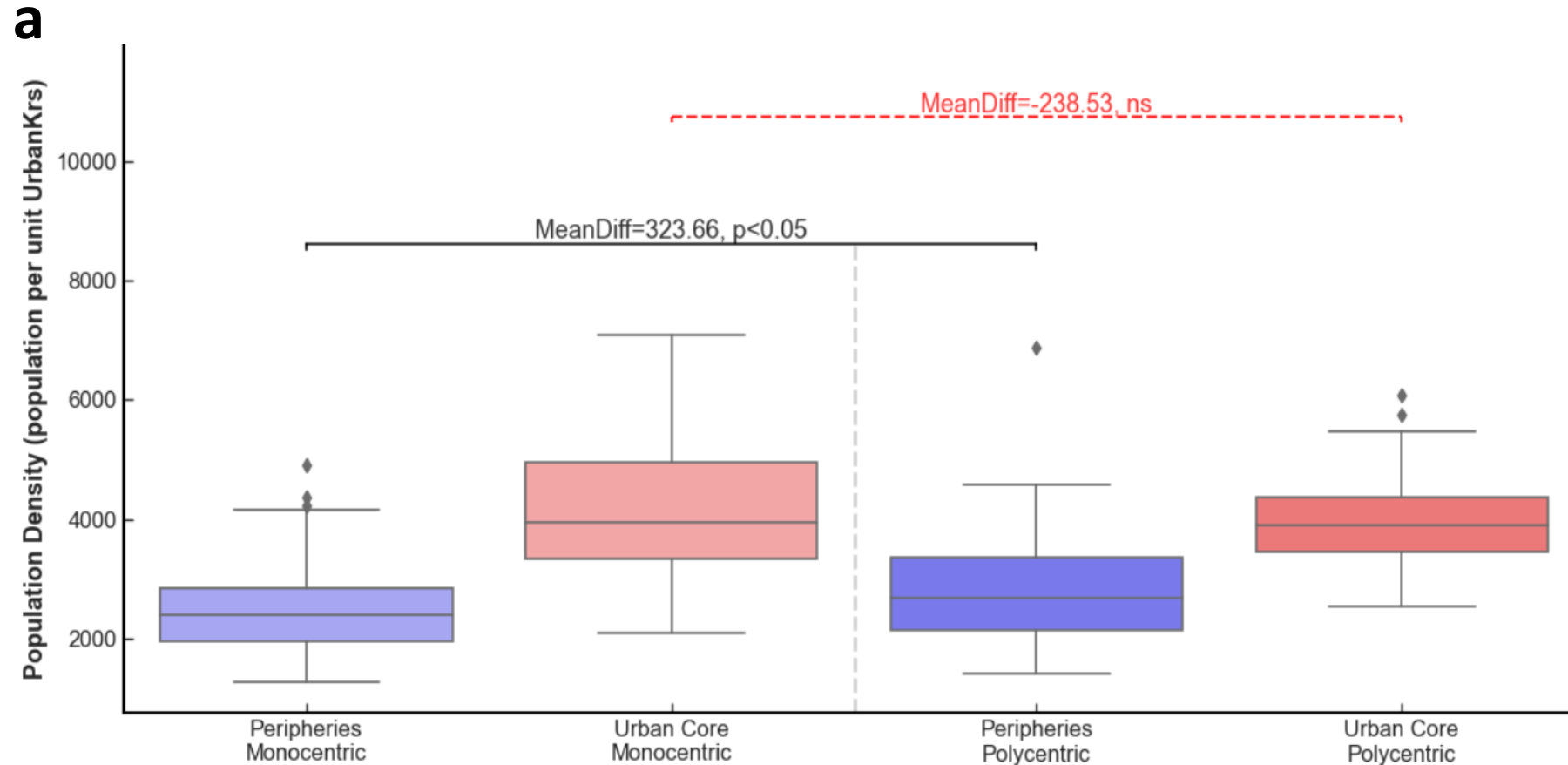
Questions and Comments

Thank you!

Contact info:

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Mechanism analysis I – population density and region size



a: Comparison of **density** across monocentric and polycentric regions

- **Urban core(s):** no significant differences
- **Peripheries:** density of peripheries in PURs > density of peripheries in MURs