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Environmental sustainability in polycentric urban regions: an urban resilience perspective

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ABSTRACT

Regional studies research examining the environmental impacts of polycentric urban structures is often called for, but remains scarce. This study uses urban resilience theory to conceptualise, methodologically specify and empirically assess the effects. We develop an evaluation system to establish a regional environmental sustainability index and apply it to urban regions across China. Gridded population datasets and inter-city co-patent data proxy morphological and functional polycentricity. Results show that morphological polycentricity positively impacts environmental sustainability, while functional polycentricity only positively affects public stewardship in environmental protection. Urban resilience attributes such as diversity and flexibility have uneven explanatory power on these dynamics.

KEYWORDS

environmental sustainability; polycentricity; urban resilience; urban regions; China

JEL R3, R30

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1. INTRODUCTION

It has been argued that cities as complex systems face unprecedented risks, ranging from natural catastrophes to economic crises and pandemics (Xu et al., 2023). While often localised, these risks also affect larger regional urban systems, as cities are inextricably linked to their surrounding regional environments by all kinds of flows, interactions and networks (Harrison et al., 2023). This interdependence multiplies the potential impact of risks on the regional scale (Finka & Kluvánková, 2015). For instance, air pollution has become a regional issue as it spreads beyond individual cities via transportation networks (Chen et al., 2021b). Polycentric urban regions (PUR), defined as urban clusters consisting of several physically proximate and functionally interconnected cities (Humer et al., 2022), exhibit a specific, often densely networked, regional structure. As PURs have emerged as a dominant form of regional spatial organisation, there have been growing concerns about their regional vulnerability to environmental risks.

Environmental sustainability can be defined as 'the long-term maintenance of valued environmental resources in an evolving human context' (Esty et al., 2005, p. 15; Organisation for Economic Co-operation and Development (OECD), 2001). It is a central consideration in evaluating the consequences of polycentric development because polycentric urban structures are often framed as a relevant planning concept to achieve environmentally sustainable development (e.g., European Spatial Planning Observation Network (ESPON), 2004). Polycentric urban development has been embraced as a strategy for environmental management in different parts of the world, evidenced by its adoption in initiatives such as the European Gothenburg Council (Vandermotten et al., 2008), the PlanMaryland programme in the United States (Knaap et al., 2016) and the formulation of Master Plans for megacities in China (Li, & Zhou, 2019).

However, the theoretical underpinnings and empirical corroboration of this assumed impact are insufficiently developed. In terms of theoretical underpinnings, it is clear that two types of theoretical rationales undergird this impact. The first rationale, rooted in the concept of externalities, posits that polycentric development can help mitigate negative environmental externalities – such as air pollution and habitat destruction – by dispersing economic activities across space (Veneri, 2010). Based on the concept of compact cities, the second rationale conceptualises PURs as 'a series of compact cities' (Jenks et al., 2013, p. 6), benefiting from sustainability advantages such

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as high density, mixed land use and transport efficiency. By combining both advantages, PURs are argued to be 'manageable and possible to plan in a more sustainable way' (p. 6). At the same time, this vantage point overlooks two other potential factors: the evolutionary nature of PURs; and the intricate interactions among their constituent cities.

In terms of empirical corroboration, exploration and validation of these conceptual ideas have been uneven. For instance, some studies suggest that polycentric development increases PM2.5 pollution (Qiang et al., 2023) and deteriorates thermal environment (Yue et al., 2019), while others argue that polycentricity goes hand in hand with enhanced CO_2 emission efficiency (Sha et al., 2020), improved air quality (Li & Zhou, 2019) and reduced surface urban heat island intensity (Han et al., 2022). In addition to these structural–quantitative analyses, other research examined how policy actors exploit opportunities afforded by polycentric urban forms to secure environmental policies, such as the international climate policy initiated by the European Union (EU) (Rayner & Jordan, 2013). However, these analyses have mainly focused on particular environmental indicators or policies at the scale of individual cities. Furthermore, as Esty et al. (2005, p. 10) argued, environmental sustainability encompasses more than environmental qualities: it also involves 'the capacity to maintain or enhance conditions in the years ahead' for the entire region.

Against this background, in this paper we argue that the *urban resilience* concept may provide new insights into the environmental sustainability of polycentric urban systems. Urban resilience refers to the ability of urban systems to maintain or restore the required functions in the event of disasters, to adapt to change and to transform systems that limit current or future adaptability (Meerow et al., 2016). PURs are complex urban systems constantly undergoing change and evolution, and urban resilience provides a framework for conceptualising, measuring, and guiding this change and evolution. Moreover, critical attributes of urban resilience, such as *complexity*, *redundancy* and *diversity* (Eraydin, 2013), are crucial in understanding how polycentric structures affect environmental sustainability. Here, we employ resilience thinking to elucidate the potential relationships between urban polycentricity and environmental sustainability.

More specifically, we aim to answer two research questions:

- To what extent does polycentric development impact environmental sustainability?
- How can we theoretically capture this impact?

To illustrate our approach, we focus on 19 urban regions (URs) in China where the central government has actively embraced polycentric development as a regional planning strategy (Wu, 2016). China stands as a country with high energy consumption (Zhang & Du, 2023), and its national environmental performance index,[1] as calculated by the Yale Centre for Environmental Law and Policy in 2022, ranks near the bottom globally. This makes China's URs an interesting empirical setting for exploring some of the ideas developed in this paper.

The remainder of this paper is organised as follows. Next, we synthesise the literature discussing polycentric development and environmental sustainability in relation to urban resilience theory. We then present our analytical approach, including our measurements of polycentricity and environmental sustainability and the statistical techniques to analyse their evolving relationships. We then discuss whether and how our results indicate that polycentric development is indeed associated with (different dimensions of) environmental sustainability. We conclude by discussing insights for policymakers and the wider environmental sustainability community.

2. LITERATURE REVIEW

2.1. Policy narratives, definitions of environmental sustainability and key elements

Environmental sustainability is often included among the multiple objectives associated with polycentric development in territorial planning alongside economic growth and social cohesion. Still, it remains vaguely defined or subsumed under broader sustainability goals. The European Spatial Development Perspective (ESDP) (1999) integrates environmental sustainability within its overarching vision of sustainable development, describing it as 'environmentally sound economic development that preserves present resources for use by future generations' (p. 10). ESPON (2004) provided greater clarity by emphasising the importance of cohesion policies to foster more balanced and sustainable territorial development. It identifies specific environmental goals, such as 'the conservation of natural resources and cultural heritage' (p. 4), while promoting 'more balanced competitiveness of the European territory'. Over time, these objectives have expanded to address broader challenges, including climate change, sustainable energy and nature conservation, as highlighted in the EU Territorial Agenda 2030 (2030). Similar narratives linking polycentric development and environmental sustainability are evident in other regions, albeit less explicitly. For instance, China's New-Type Urbanisation Development Plan (2014–2020) advocates for the coordinated development of large, medium and small cities, emphasising long-term benefits in 'improving environmental quality, protecting ecological environments, and reducing energy consumption'.

These and related strategic documents share several elements in their environmental goals, which revolve around three key pillars: security (ensuring essential resources for life, health and stability), harmony (achieving a balanced coexistence between humans and nature) and dynamism (addressing the needs of both present and future generations) (Moldan et al., 2012). These pillars align with Goodland's (1995) widely cited definition of environmental sustainability, which describes it as societal efforts to 'improve human welfare by protecting the sources of raw materials used for human needs and

ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans' (p. 3). Our research adopts Goodland's definition as its foundational theoretical framework, using it to inform both the analysis and the construction of the indicator index (see sections 2.3 and 3.3 for further details).

2.2. Theoretical perspective on the environmental implications of polycentricity

Few studies have empirically linked urban polycentricity to the broader framework of *environmental sustainability*. Most research instead focuses on specific dimensions such as traffic congestion (Li et al., 2021), greenhouse gas emissions (Qiang et al., 2023) and resource consumption (Ding & Luo, 2024). While these studies provide valuable insights, they often lack a clear articulation of the theoretical foundations underpinning their frameworks. This subsection summarises key theoretical perspectives on the environmental implications of polycentric development, highlighting their contributions and limitations, and identifies the theoretical approach adopted in this research.

Studies addressing the environmental implications of polycentricity can be categorised into three interconnected theoretical perspectives. The first is the *geographical* perspective, which focuses on the spatial structure of polycentric urban systems, particularly the distribution and interaction of urban centres. This body of research emphasises how polycentric structures promote regional balance by avoiding over-concentration in a single centre. By fostering interconnected networks of urban centres, these structures enable the efficient sharing of resources, services and infrastructure, reducing pressures such as congestion and resource depletion (Qiang et al., 2023). Closely linked to this is the *land-use* perspective, which focuses on the physical aspects of urban expansion. This perspective associates polycentric development with concentrated expansion and high population densities. Such configuration reduces per capita land consumption and transport-related energy use, leading to more resource-efficient urbanisation patterns (Dong et al., 2019). The third and most widely adopted perspective is the *economic* perspective (Burger et al., 2014), which considers polycentric development as a means to mitigate the economic costs of urbanisation (e.g., congestion, emissions) by distributing economic activities more evenly. The perspective often intersects with the environmental Kuznets curve theory, which suggests that environmental degradation intensifies during the early stages of economic development but diminishes as economies mature (Dadashpoor et al., 2023). While this perspective implicitly links polycentric development to economic growth – and, by extension, environmental improvements (Qiang et al., 2023) – this connection remains contested (e.g., Caset et al., 2023).

These theoretical foundations primarily focus on preserving or consuming resources, lacking a dynamic understanding of how PURs can evolve sustainably over time. As defined above, environmental sustainability emphasises the long-term maintenance of environmental resources in an evolving human context. This calls for a more holistic and long-term approach that addresses environmental dimensions and incorporates social and institutional elements, such as governance structures, collaborative framework and equitable access to resources, which can influence future resource use trajectories. This research aims to bridge these gaps by adopting an alternative conceptual toolbox – urban resilience – to discuss how PURs can adapt, transform and sustain themselves in the face of evolving challenges.

2.3. Urban resilience: a conceptual bridge between urban polycentricity and environmental sustainability

The concept of urban resilience originates from the broader notion of 'resilience', introduced by Holling (1973). As an ecologist, Holling defined resilience as the 'measure of the ability of systems to absorb changes of state variables and still persist' (p. 17). This theory has since transcended ecology, with applications in disciplines as varied as economics, engineering and, more recently, urban studies. Consistent with the overarching definition of 'resilience', urban resilience seeks to understand urban systems exposed to a broad range of risks and constantly go through the processes of evolution and transformation (Sharifi, 2019). While urban resilience has been primarily applied at the meso-level, such as building blocks and neighbourhoods, Sharifi (2019) advocated for its extension to the macro-scale, such as cities and regions. This perspective resonates with our approach, as PURs are inherently complex systems characterised by multiple urban centres, interconnected infrastructures and dynamic socio-economic interactions. Urban resilience offers a lens through which we can conceptualise the relationships between urban polycentricity and environmental sustainability.

Six attributes, namely *critical mass*, *redundancy*, *diversity*, *flexibility and adaptability*, *complexity* and *social cohesion* (Cruz et al., 2013), are particularly pertinent here. These attributes encompass both morphological and functional aspects of polycentricity, with some emphasising spatial configurations and others prioritising functional interactions, and several addressing both. These attributes and implications are illustrated in Figure 1, which provides a conceptual framework linking urban resilience to PURs:

- *Critical mass*: this first attribute primarily pertains to the morphological aspect of PURs (Figure 1). It involves pooling resources to share facilities and services in PURs (Cruz et al., 2013), which leads to the optimisation of resource utilisation and minimising waste. For instance, shared infrastructures such as transport networks, water systems and waste management facilities can serve a large population base, leading to economies of scale and improved resource allocation.
- *Redundancy*: polycentric development may also provide redundancy in urban structures. With multiple urban centres distributed across space, alternative nodes exist for resource distribution and services such as water,

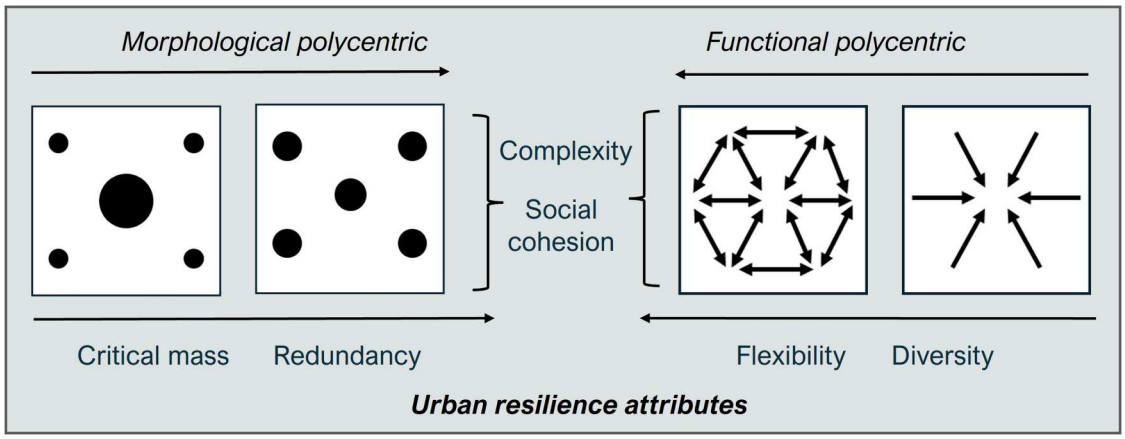

Figure 1. Urban resilience attributes with polycentric development in urban regions (URs).

energy and waste management (Figure 1). This redundancy can enhance regional resilience by dispersing potential risk and distributing it among subcentres (Sharifi, 2019). It helps avoid significant damages, especially from rapid-onset disasters, in case of a high concentration of people and resources in a limited space.

- *Flexibility and adaptability*: these indicate the ability to rearrange urban structures and functions when facing disruptions (Sharifi, 2019). This aspect focuses more on the functional aspect of PURs (Figure 1). PURs have multiple urban centres with diverse functions, allowing each to be less dependent on the system as a whole. This helps maintain equilibrium when disturbances occur, as other centres can provide functionality to the whole region. For example, in the event of contamination of the water supply of one urban centre in PURs, alternative water resources from other centres can ensure continued access to clean water for residents.
- *Diversity*: similar to flexibility, diversity also plays a crucial role in enhancing urban resilience by fostering various urban structures and functions. Within PURs, diverse urban centres offer many possibilities for multiple habitats, species and ecological processes to thrive. As Walker and Salt (2012, p. 145) suggested, 'the more diversity, the better the capacity for a system to adapt to a wide range of different and sometimes unpredictable circumstances'.
- *Complexity*: the complexity of urban structures lies in both the morphological and functional aspects (middle part of Figure 1). PURs are open and multilayered complexes of nodes, networks, flows and interactions. In addition, distinct but closely located cities in PURs relate to each other in a synergetic way, making networks of cities more than just the sum of their parts (Meijers et al., 2018). These interactions and synergies facilitate knowledge exchange and collaborative initiatives addressing shared environmental challenges.
- *Social cohesion*: finally, social cohesion is also both a morphological and a functional attribute of PURs. The presence of diverse urban centres and their frequent interactions supports social interaction, cultural diversity, and social capital, strengthening community ties and collective action for environmental stewardship.

All six dimensions are closely connected to the development of environmental sustainability, each addressing distinct but interconnected aspects. For instance, the critical mass attribute aligns with the conservation of the environmental system through its role in optimising resource utilisation (one of the components of the regional environmental sustainability index, as outlined in section 3.3). Similarly, redundancy and flexibility are linked to reducing human vulnerability by enhancing the capacity to manage disruptions (another index component). Meanwhile, the social cohesion attribute is inherently tied to public stewardship, emphasising collective action and environmental awareness. Given the challenges in quantifying these six attributes and their often-overlapping effects, we ground our discussion within this theoretical framework. From this foundation, we formulate the following hypotheses, which guide our research:

> *Hypothesis 1: Morphological polycentric development fosters environmental sustainability in URs, both in general and across specific sub-dimensions.*
>
> *Hypothesis 2: Functional polycentric development fosters environmental sustainability in URs, both in general and across specific sub-dimensions.*
>
> *Hypothesis 3: The combined effect of morphological and functional polycentricity collectively leads to an enhanced, positive impact on environmental sustainability in URs.*

We will revisit these attributes, the broader concept of urban resilience and the hypotheses in the results section.

2.4. Review of existing analytical frameworks

Empirically validating hypotheses linking polycentricity and environmental sustainability requires comparable building blocks. However, existing frameworks addressing either concept lack clarity or are often difficult to

operationalise (Möck & Küpper, 2020; Salas-Zapata & Ortiz-Muñoz, 2019), while combining both perspectives compounds this validation process. Thus, we advocate a coherent approach to empirically operationalising these elements. In this subsection, we review previous literature to inform our analytical framework.

In studies assessing the impact of polycentricity on the environment, researchers typically adopt a morphological perspective to polycentricity. Data include information on population distributions from LandScan (Sha et al., 2020) or higher resolution satellites (Qiang et al., 2023), employment (Han et al., 2022) or impervious surfaces[2] (Li et al., 2024). These indicators present areas of intense human activities that may influence thermal radiation, surface temperature or other environmental factors, depending on the specific environmental indicator adopted. In contrast, functional polycentricity research is often limited by data availability. An exception is Yue et al. (2019), who use night-time light intensity to define urban centres as functional hubs in an urban system. Another approach was introduced by Veneri (2010), who used daily work commute data between Italian municipalities to examine the impact of commuting patterns on greenhouse emissions. Both studies explain that environmental emissions can be affected by shifts in population distribution, functional orientation and commuting patterns.

These studies, however, typically rely on single environmental indicators, offering a simplified representation of the environmental system that may not be suitable for complex and evolving regional contexts. We broaden our perspective by examining the broader environmental and economic geography literature and identifying two relevant considerations: the scale of the analysis and the design of the evaluation system. The first concern derives from the observation that environmental sustainability assessment techniques[3] mainly concentrate on two scales: local (e.g., product material flow analysis) and national (used for global comparison) (e.g., sustainable development indicators of Eurostat, environmental performance index (EPI)) (Wolf et al., 2022). Until recently, the regional scale in between has often been left out. With some groups of researchers developing regional indices (e.g., Smetana et al., 2015; Wang et al., 2022a), the second consideration comes to the fore: how to downscale/upscale the evaluation system constructed at the national/local scale? As outlined by Smetana et al. (2015), regional impact assessment differs from local and national impacts, as it should (1) include more resource types in the system (than local analyses) and (2) characterise regional differentiations to provide higher accuracy (than national analyses).

Against this backdrop, our research aims to develop a systematic framework to assess environmental sustainability at the regional level and link it to urban polycentricity. Our framework focuses on two critical elements:

- Index adaptation: we explore the feasibility of adapting national environmental sustainability indexes, such as Esty et al. (2005), to regional contexts. Our analysis covers a broad spectrum of factors, focusing on *resource availability and utilisation*, *regional ecosystems vulnerabilities* and *public awareness*, arguably the highest priorities for sustainability assessments at the regional scale (Smetana et al., 2015).
- Polycentric structure evaluation: we evaluate URs' morphological and functional polycentricity using gridded population datasets and intercity patent cooperation data, respectively. In so doing, we link morphological polycentricity with environmental sustainability in a 'practical' manner, assuming that population distribution data reveal the spatial organisation of human settlements, which are more related to the tangible aspects of environmental sustainability. In contrast, functional polycentricity is linked with environmental sustainability in a more 'cognitive' way, as patent cooperation data unveil the dissemination of intangible technologies, knowledge and innovation across cities, which may be related to the intellectual aspects of environmental sustainability.

3. RESEARCH AREA, DATA AND METHODS

3.1. Research area

Our analyses focus on the 19 URs in China identified in the National New-Type Urbanisation Plan (2014–2020) (Figure 2). These URs are relevant to China's territorial development strategy. Despite occupying only 29% of the national land area, in 2018, these regions covered 68% of the total population and 83% of China's gross domestic product (GDP). However, they also present highly fragile eco-environmental locations characterised by densely concentrated populations and intense human activities (Fang & Yu, 2020). For more detailed information about these URs, see Appendix A in the supplemental data online.

3.2. Data

Our research uses three complementary datasets. First, we compile a broad array of environmental and socio-economic data for these URs (e.g., PM2.5 concentration, forest coverage, GDP, etc.) from diverse sources, including the National Earth System Science Data Centre, China City Statistical Yearbooks and China Urban database (2005–2017). Second, we use the LandScan High-Resolution Global Population Dataset (2005–2017) to measure the degree of polycentricity of URs from a morphological perspective. This dataset provides an ambient (average over 24 h) global population distribution at approximately 1 km spatial resolution. Third, we use co-patent data from incopat.com to measure polycentricity from a functional perspective. This dataset comprises patents of all industries, which involve two or three applicants who could be individuals, firms, universities or research institutes. Our analysis zooms in on intercity collaborations within URs by using the information of applicant

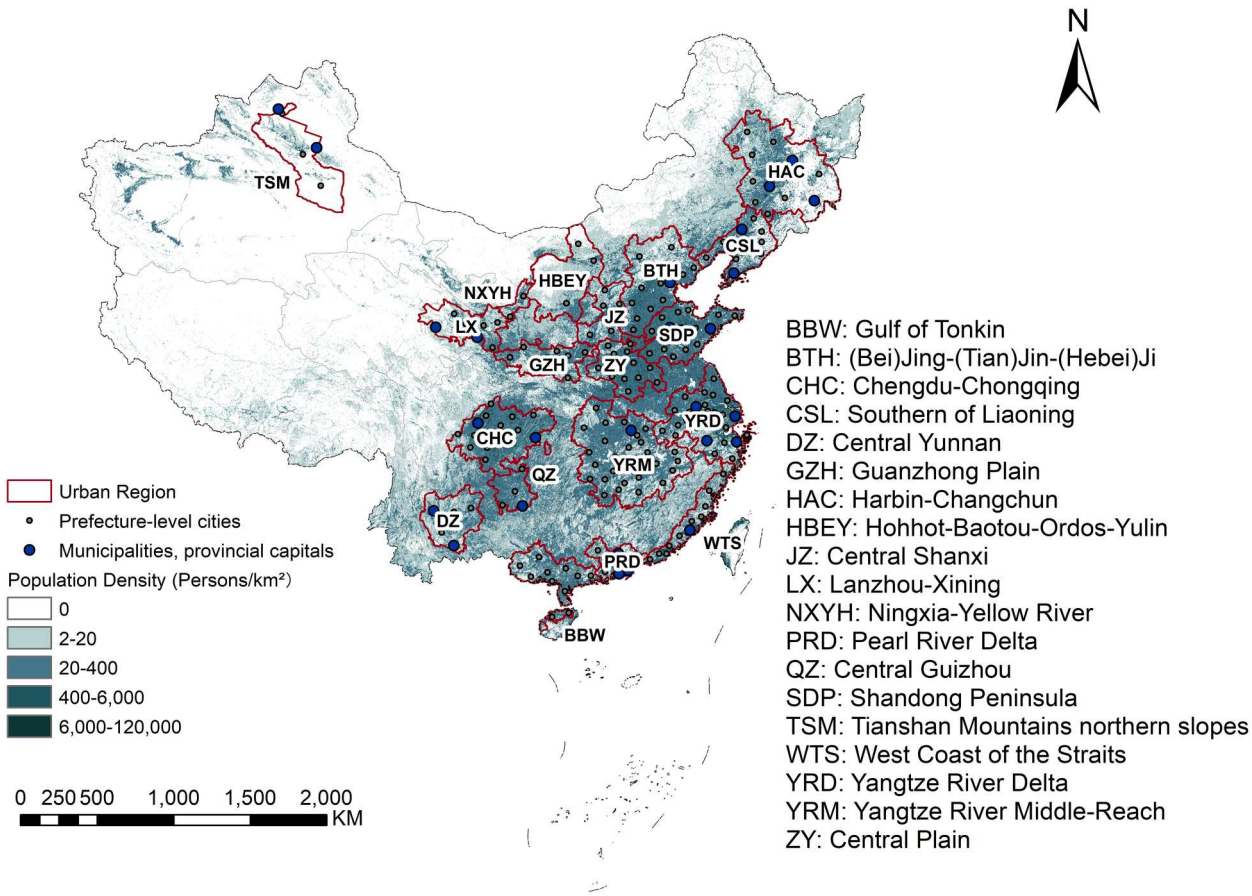

Figure 2. Urban regions (URs) in China identified in the National New-Type Urbanisation Plan (2014–2020).

addresses. The dataset covers inter-city co-patents over 13 years from 2005 to 2017, comprising 784,039 records.

3.3. Methods

3.3.1. Constructing a regional environmental sustainability index (RESI)

Our RESI quantifies how likely a UR is to effectively preserve its valuable environmental resources over time. Drawing on previous studies (Cook et al., 2017; Esty et al., 2005) and the indexation criteria of availability, completeness and relevance, we develop an indicator system for RESI (Table 1), comprising five key components.

First, the *environmental systems* reflect the state of natural and environmental systems, assessed through air, water and eco-environment quality measures. Second, *reducing environmental stresses* evaluates the pressure exerted on environmental systems due to resource utilisation, encompassing factors such as lowering ecosystem stress, energy consumption efficiency and reducing waste pressure. Third, *reducing human vulnerability* assesses human vulnerability to environmental change, considering both environment-related natural disaster vulnerability and human vulnerability. The fourth component, *institutional capacity*, assesses institutional responses to environmental challenges, focusing on environmental governance, personnel deployment and basic human sustenance. Finally, *public stewardship* assesses society's capacity to manage environmental stresses and citizens' awareness of environmental sustainability. This component is measured through greenhouse gas emissions and public awareness of environmental sustainability.

We select two to three indicators for each component to evaluate its performance and apply the entropy method to calculate the integrated RESI score for URs. The selection of indicators follows two key principles outlined in section 2.4: (1) incorporating a diverse range of resource types, including water, air, forest and energy, to provide a more comprehensive assessment than is typical in local systems; and (2) capturing regional variations to ensure greater accuracy and relevance compared with generalised national-scale measures. For instance, indicators such as eco-environmental quality, environmental governance and public awareness are specifically tailored to reflect region-specific dynamics, overcoming the limitations of aggregated indices often used in national frameworks, such as those for evaluating progress toward the United Nations' (UN) Sustainable Development Goals (SDGs).

3.3.2. Measuring urban polycentricity

We adopt the method used by Zhang and Derudder (2019) to measure morphological and functional polycentricity. For detailed illustrations of these methods, using the example of the Yangtze River Delta (YRD), see Appendix B in the supplemental data online.

Table 1. Regional environmental sustainability index (RESI) building blocks.

Component	Type	Indicator	Property[a]	Sources
Environmental system (ES)	Air quality	Per capita annual mean concentration of PM2.5 ($\mu g/m^3$)	–	China Urban Statistical Yearbook
	Water quantity	Per capita water resources per year (10^7 litres)	+	China Urban Construction Statistical Yearbook, China Urban Statistical Yearbook
	Eco-environmental quality	Integrated index derived from Landsat surface reflectance data, calculated by the factors of greenness, dryness and heat (%)	+	National Earth System Science Data Centre
Reducing environmental stress (RE)	Reducing ecosystems stress	Annual change in forest cover (%)	+	National Tibetan Plateau/Third Pole Environnement Data Centre
	Energy consumption efficiency	Supply of electricity, coal, natural gas and liquefied petroleum gas (converted to coal) (%)	+	China Urban Statistical Yearbook, Statistical Yearbooks of Provinces, and Statistical Bulletins of Prefecture-level Cities
	Reducing waste pressure	Proportion of consumption wastes treated (%)	+	China Urban Statistical Yearbook
Reducing human vulnerability (HV)	Environment-related natural disaster vulnerability	Proportion of area affected by natural disasters to the total urban area (%)	–	Statistical Yearbooks of Provinces
	Human vulnerability	Proportion of deaths due to natural disasters to the total urban population (%)	–	China Urban Statistical Yearbook
Institutional capacity (IC)	Environmental governance	Frequency of terms related to 'environmental protection' in the municipal government work reports (%)[b]	+	Municipal Government Work Reports
	Personnel deployment	Proportion of employed personnel in the water conservancy and environment industry to the total employed personnel	+	China Urban Statistical Yearbook
	Basic human sustenance	Number of hospital beds per thousand people (n)	+	China Urban Statistical Yearbook
Public stewardship (PS)	Greenhouse gas emission	Per capita carbon emission (metric tonnes)	–	China Urban Statistical Yearbook
	Public awareness of environmental sustainability	Search frequency on the Baidu search engine for the keyword 'environmental pollution' (%)[c]	+	Website of the Baidu Index

Note: [a]A '+' indicates positive indicators for which bigger values are better, while a '–' refers indicators for which smaller values are better.
[b]The frequency of occurrence of environmental words in government documents is widely used as a measurement for environmental regulation strength. We use the keyword 'statistical method' to analyse the text of municipal government work reports. The keywords we choose include '*huanbao*' (environmental protection), '*wuran*' (pollution), '*nenghao*' (energy consumption), '*jianpai*' (emission reduction), '*wuranwupaifang*' (discharge of pollutants), '*shengtai*' (ecology), '*lvse*' (green), '*ditan*' (low carbon) and '*huaxuexuyangliang*' (chemical oxygen demand).
[c]We use the Baidu Search Index (BSI) to quantify the public's attention to the environment. BSI is a weighted value of search frequency on the Baidu search engine for a certain keyword on the basis of Internet users' search volume.

Morphological polycentricity is calculated as:

$$POLY\_M_i = 1 - \frac{\sigma_m}{\sigma_{mmax}} \quad (1)$$

where $POLY\_M_i$ indicates the degree of morphological polycentricity of UR i; σ_m represents the standard deviation (SD) of the total population of urban centres in cities across UR i; and σ_{mmax} is the SD in a hypothetical two-city UR where one city has no population and the other has the maximum observed population.

Urban centres are identified based on the following procedure. First, drawing on the LandScan population

dataset, we generate a density file for individual cities, where individual grids are ranked based on population density. Second, following Liu et al. (2016), we set a density cut-off at the city's 95th percentile gridded population and select the 5% most densely populated grids. In the third step, grids that are eight-adjacent to each other are combined into clusters. Finally, we retain clusters covering at least 3 km^2 and containing more than 100,000 inhabitants as 'urban centres'.

Functional polycentricity is calculated as:

$$POLY\_F_i = \left(1 - \frac{\sigma_f}{\sigma_{fmax}}\right) * \Delta \quad (2)$$

where $POLY\_F_i$ indicates the degree of functional polycentricity of UR i; σ_f is the SD of cities' functional connections (represented by degree centrality CD) in UR i; and σ_{fmax} is the SD of degree centrality of a two-city UR where one city's degree centrality equals 0 and the others' equals the highest. Δ is the network density of UR i, defined as the ratio of the total intercity connections to the maximum of intercity connections that is theoretically possible. We use city-pair co-patent data across all industries to measure intercity connections.

Degree centrality is calculated as follows:

$$CD_m = \sum_n^k S_{mn} \quad (3)$$

where CD_m denotes the degree centrality of city m in UR i; k indicates the number of cities in UR i; and S_{mn} denotes the co-patency counts between city m and city n in UR i.

3.3.3. Econometric model

We use a fixed-effects panel data model (FE) to test the influence of urban polycentricity on regional environmental sustainability. We formulate the following baseline regression model:

$$Ln(ESI_{it}) = \delta + \alpha Ln(POLY\_M_{it}) + \beta Ln(POLY\_F_{it}) + XLn(\theta) + \gamma_t + \delta_i + \varepsilon_{it} \quad (4)$$

The main variables of interest are $POLY\_M_{it}$ and $POLY\_F_{it}$, morphological and functional polycentricity degree. X represents a vector of control variables, including the UR's economic development level (GDP per capita, GDP), population density (the number of people per unit of urban area, POP) and industrial structure (the ratio of GDP in the secondary industry to that of tertiary

Table 2. Fixed effect (FE) result of the influence of polycentricity on regional environmental sustainability index (RESI).

Variable	1	2	3	4	5	6
Intercept	0.22	0.27	0.42	0.13	0.13	0.28
	(0.10)**	(0.09)**	(0.01)***	(0.21)	(0.21)	(0.06)***
POLY_M		0.34	0.81			0.30
		(0.06)***	(0.09)***			(0.08)**
POLY_M^2			2.54			
			(0.36)***			
POLY_F				−0.07	−0.08	−0.08
				(0.02)**	(0.05)*	(0.05)*
POLY_F^2					0.33	
					(0.48)	
*POLY_M*F*						−0.14
						(0.06)**
POP	−0.18	−0.22	−0.26	−0.22	−0.22	−0.23
	(0.01)***	(0.01)***	(0.01)***	(0.05)**	(0.06)**	(0.01)***
PGDP	0.11	0.11	0.07	0.06	0.06	0.14
	(0.01)***	(0.01)***	(0.01)***	(0.02)*	(0.02)**	(0.02)***
IND	−0.20	−0.08	−0.00	−0. 23	−0.23	−0.08
	(0.08)**	(0.07)	(0.06)	(0.11)***	(0.06)**	(0.04)*
R^2	0.57	0.60	0.63	0.62	0.62	0.68
Average VIF	1.12	1.83	2.72	1.18	1.36	1.59
Breusch–Pagan	0.15	0.41	0.58	0.03	0.00	0.02
Wooldridge test	0.33	0.32	0.32	0.12	0.15	0.12
AIC	−560.99	−572.39	−597.77	−599.47	−597.63	−608.67
Observations	247	247	247	247	247	247

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors are shown in parentheses. AIC, Akaike information criterion; VIF, variance inflation factor.

industry, *IND*). γ_t is the individual fixed effect. δ_i is the time-fixed effect; ε_{it} is the error term; and α, β, θ are the parameters to be estimated. All these variables are log-transformed to ensure a linear form.[4]

Before presenting our empirical results, we also deal with the standard range of econometric issues. The panel unit test results suggest stable relationships between variables (see Appendix D in the supplemental data online). 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. For the descriptive statistics of these variables, see Appendix C in the supplemental data online.

4. RESULTS

4.1. Profile of urban polycentricity and environmental sustainability in URs

Before discussing the regression results, we visualise the data to provide an introductory profile of URs in terms of their polycentricity and the RESI (Figure 2).

4.1.1. Coordination of polycentricity and RESI

Figure 2a displays a two-dimensional quadrant where individual URs are plotted based on their scores of morphological and functional polycentricity, with the colour of the circles indicating their RESI scores. These URs are divided into four quadrants centred on the means. Our results show a divergence between the morphological and functional dimensions of polycentricity and their relationships with RESI. The upper right quadrant displays URs with high morphological and functional polycentricity, including the URs of the Yangtze River Delta (YRD), Pearl River Delta (PRD), Bei(jing)–Tian(jin)–Hebei(ji) (BTH) and Shandong Peninsula (SDP). These URs, as extensively documented in the literature (e.g., Liu et al., 2016), were the first in China to develop centrally coordinated and locally initiated region plans. They are amongst the nation's most developed and economically competitive URs, characterised by mutually complementary central cities and intensive knowledge cooperation.

Most of China's URs are in the lower right quadrant, where URs are morphologically polycentric but functionally less so (relative to the sample average). Compared with Chen et al. (2021a), who found that most URs in 2015 exhibited lower levels of both morphological and functional polycentricity, our results suggest an evolution towards greater morphological polycentricity. However, functional connectivity remains limited in terms of knowledge transfer represented by patent cooperation. According to Liu et al. (2016), this polycentricity profile reflects a mismatch between governmentally designated and economically integrated URs. For example, the Yangtze River Middle-Reach (YRM) includes multiple large municipalities aiming for regional integration, but patent cooperation is concentrated among provincial cities. The remaining two quadrants, which contain URs that are either less morphologically and functionally polycentric or only functionally polycentric, include only four URs. These URs typically have a primate urban system, where the principal cities amass most population, economic activities and external connections.

We find no significant bivariate correlations between RESI and polycentricity indexes. RESI scores are universally low, with the highest in the Tianshan Mountains Northern Slopes (TSM) and Ningxia–Yellow River (NXYH), regions that exhibit moderate morphological polycentricity but low functional polycentricity. In particular, URs in the first quadrant with high morphological and functional polycentricity show lower RESI scores, contrary to our expectations. We will explore this further by examining the sub-dimension of the RESI score and considering a range of control variables.

4.1.2. Temporal characteristics of RESI and sub-dimensions

Figures 2b–c show the sub-dimension and total scores, respectively, for the RESI for URs in 2005 and 2017. They show a slight decrease in the total score across URs over the study period. The TSM and West Coast of the Straits (WTS) have the highest RESI scores, while BTH and SDP have significantly lower RESI scores. Regarding sub-dimensions, there is no significant variance in human vulnerability (HV) across URs and over time. The main contributions to RESI score variance are reducing environmental stress (RE) and environmental system (ES). Turning to the performance of individual URs, WTS and YRM have managed to control air pollution and provide basic human water resources, thus leading to high RE scores. Meanwhile, WTS and TSM lead in expanding forest coverage and utilising resources efficiently, contributing to high ES scores. For institutional capacity (IC) and public stewardship (PS), nearly all URs show increased scores over the period, indicating improved institutional capacity and public awareness in addressing environmental challenges.

4.1.3. Spatial characteristics of polycentricity and RESI

We also present maps to visualise the spatial distribution of these elements. Figures 2d–f depict the spatial distribution of URs regarding morphological and functional polycentricity and the RESI, respectively. They show a significant downward trend from coastal to inland URs regarding polycentricity indexes, particularly functional polycentricity, with PRD and YRD significantly standing out. This trend aligns with the notion that coastal regions are more financially supported, economically developed and open to cooperation. In contrast, a reverse trend is observed in the RESI, where inland URs score higher, followed by central and coastal URs (Figure 3).

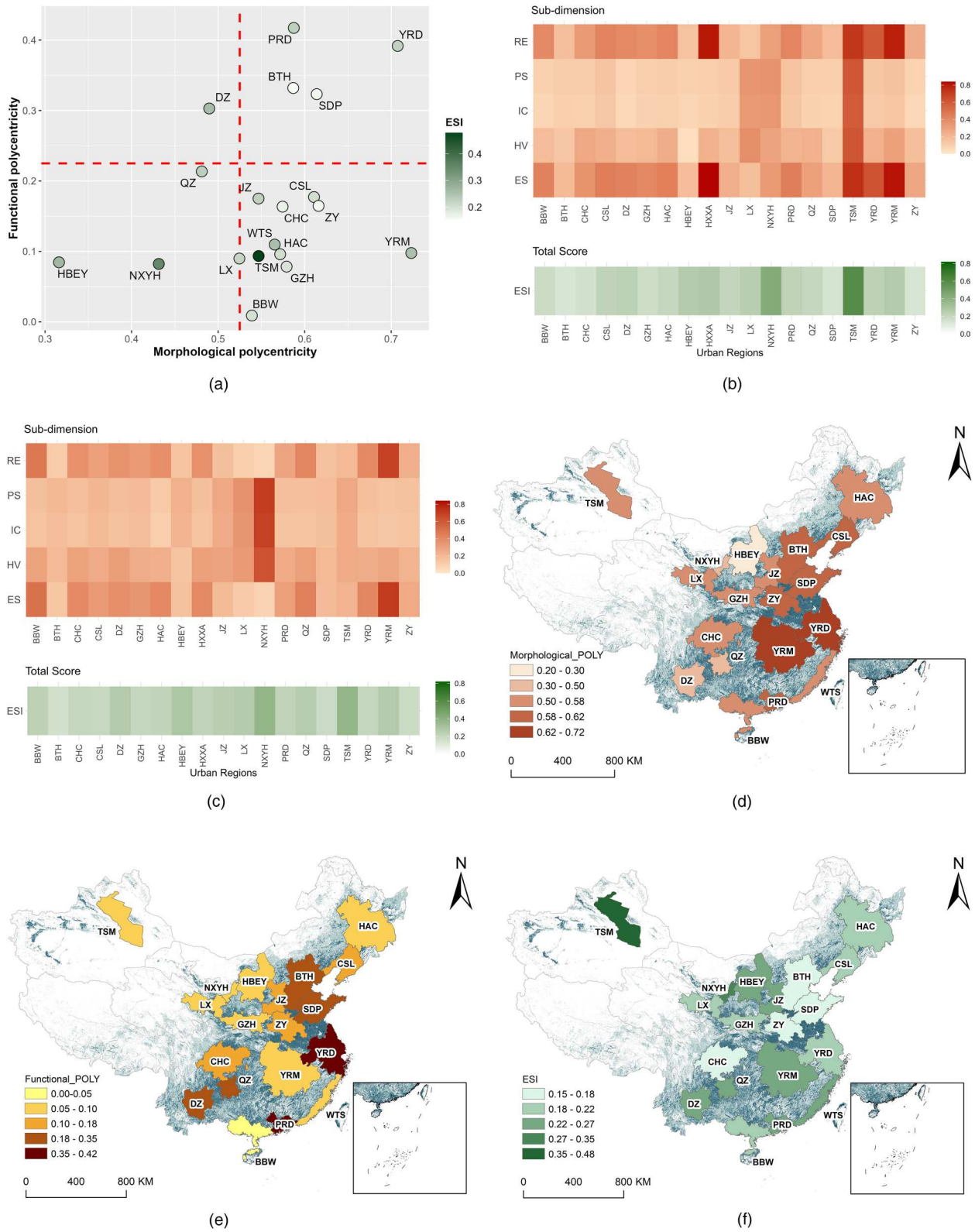

Figure 3. Polycentricity degree and regional environmental sustainability index (RESI) in urban regions (URs) in China: (a) scatter plot of functional versus morphological polycentricity, divided by red dashed lines at the means – circle size and colour indicate environmental sustainability index (ESI) scores; (b, c) heatmaps showing sub-dimensional scores and total ESI for each urban region under two scenarios – sub-dimensions include resource efficiency (RE), public services (PS), innovation capacity (IC), habitat value (HV) and ecological security (ES); (d, e) thematic maps of morphological and functional polycentricity across China, using colour gradients to indicate intensity; and (f) thematic map of ESI values by urban region. All maps include urban region labels and insets showing China's full extent.

4.2. Regression results

4.2.1. Polycentricity and overall RESI

We structure the discussion of our results around Table 2, employing a stepwise regression approach where variables are gradually added or replaced. Model 1 includes only the exogenous variables *POP*, *PGDP* and *IND*. In model 2, we add *POLY_M* to investigate the direct impact of *POLY_M*; while model 3 includes the square term $POLY\_M^2$ to capture possible non-linear effects. Similarly, models 4 and 5 include *POLY_F* and its square term $POLY\_F^2$, respectively. Model 6 includes the interaction term between morphological and functional polycentricity (*POLY_M*F). The relatively high R^2 across these models indicates a good fit, with all models explaining at least two-thirds of the variance in RESI across URs. We now discuss the most critical findings from the different models.

A first set of findings pertains to the control variables. We find a negative impact of both *POP* and *IND*. These findings align with our expectations. Rapid population growth has been recognised as a significant driver of environmental degradation and a threat to the sustainable use of resources. Likewise, industrialisation also increases the demand for energy usage, leading to increased environmental contamination and deteriorating environmental efficiency. Therefore, the proportion of secondary industry (mainly the industrial sectors) has a strong negative impact on RESI. In contrast, the positive impact of *PGDP* suggests that URs with better economic performance are more likely to address environmental issues proactively.

A second set of findings pertains to the independent variables of interest. The regression coefficient of *POLY_M* is significantly positive (model 2), indicating that a higher level of morphological polycentricity corresponds to a higher level of RESI. This positive relationship is further supported by including the square term $POLY\_M^2$ (model 3), suggesting a long-term positive impact of morphological polycentricity that amplifies as the degree of polycentricity increases. Therefore, our Hypothesis 1 is accepted. The results align with studies that have found positive effects of polycentric development on air quality and carbon emissions in Chinese and US contexts (Jung et al., 2024). However, our findings contrast with those of Veneri (2010) regarding resource management (land consumption and greenhouse gas emissions) in Italian regions. This discrepancy may stem from differences in regional contexts: URs in China and the United States might derive stronger environmental benefits from morphological polycentricity due to rapid urbanisation and stricter environmental regulations in recent years. In contrast, slower urban transformation in Italian regions may contribute to inefficiencies in resource utilisation, reducing the effectiveness of morphological polycentric development.

However, when examining the influence of functional polycentricity (*POLY_F*) on RESI, we find that the impact is significantly negative (model 4). The results remain consistent in model 5, which includes the square term $POLY\_F^2$. In other words, URs with higher functional polycentric degrees have a lower RESI, which leads to the rejection of Hypothesis 2. The result contradicts what Lanfredi et al. (2022) found: functionally polycentric development came with decreased land degradation in Italy. However, it aligns with Yue et al. (2019), who discovered that functional polycentricity was positively correlated with the deterioration of the thermal environment in Hangzhou, China. These contrasting outcomes likely arise from the aggregation of effects across specific environmental dimensions, a point we expand upon in the following subsection.

The final findings refer to the interaction term between *POLY_M* and *POLY_F*. In model 6, the positive impact of *POLY_M* and negative impact of *POLY_F* re-emerge, and the interaction item *POLY_M*F negatively affects RESI (model 6). Therefore, Hypothesis 3 is also rejected. This indicates that URs with higher RESI scores are morphologically polycentric but functionally less so. These findings are consistent with Figure 2, which shows that URs with a higher RESI degree exhibit moderate morphological polycentricity but low functional polycentricity. The negative interaction effect can be attributed to trade-offs that arise when both high morphological and functional polycentricity are strongly present. Morphological polycentricity helps reduce environmental stress by dispersing urban activities, whereas increased functional interdependence can offset these gains by amplifying energy use and emissions through intensified regional connectivity. This is particularly evident when functional polycentricity is measured using intercity patent collaboration, which reflects a high degree of economic and intellectual integration. Such integration often requires extensive infrastructure development, increased reliance on energy-intensive systems and, consequently, greater environmental burdens.

4.2.2. Polycentricity and sub-dimensions of RESI

The RESI captures the multiple dimensions of environmental sustainability. However, the influence of polycentricity on one sub-dimension may be offset by its influence on the other. In this section, we rerun the models with proxies of the five sub-dimensions, namely environmental system (ES), reducing environmental stress (RE), reducing human vulnerability (HV), institutional capacity (IC) and public stewardship (PS).

From models (1) to (10), the signs of the control variables remain consistent, albeit with slight differences in size and statistical significance. Overall, we find that the influences of morphological and functional polycentricity on different dimensions are uneven, with no single impact on one dimension exhibiting the same direction and/or significance:

- Environmental system (ES): morphological polycentricity is positively related to ES, while functional polycentricity is negatively associated with ES. This dimension primarily includes air pollution and water

Table 3. Fixed effect (FE) result of the influence of morphological and functional polycentricity on sub-dimensional regional environmental sustainability index (RESI).

	Morphological polycentricity					Functional polycentricity				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variable	Environmental system (ES)	Reducing environmental stress (RE)	Reducing human vulnerability (HV)	Institutional capacity (IC)	Public stewardship (PS)	Environmental system (ES)	Reducing environmental stress (RE)	Reducing human vulnerability (HV)	Institutional capacity (IC)	Public stewardship (PS)
Intercept	0.28*	1.05**	−0.02*	0.02	3.10***	0.44**	0.77*	−0.01*	−0.07	3.17***
	(0.16)	(0.31)	(0.00)	(0.15)	(0.16)	(0.19)	(0.47)	(0.01)	(0.20)	(0.13)
POLY_M	0.79***	1.07***	−0.00	−0.34**	0.18					
	(0.09)	(0.10)	(0.01)	(0.08)	(0.10)					
POLY_F						−0.38**	0.10**	0.01*	−0.16**	0.31**
						(0.14)	(0.04)	(0.00)	(0.05)	(0.12)
POP	0.02*	−0.43***	0.01*	−0.05**	−0.47***	0.11**	−0.28***	0.00	−0.09***	−0.45***
	(0.01)	(0.02)	(0.00)	(0.02)	(0.02)	(0.02)	(0.01)	(0.00)	(0.00)	(0.01)
PGDP	0.02**	−0.05	−0.01	0.06**	0.32***	0.05**	0.02	−0.01	0.05*	0.35***
	(0.01)	(0.07)	(0.00)	(0.02)	(0.04)	(0.03)	(0.05)	(0.00)	(0.02)	(0.03)
IND	−0.10	0.49*	0.00	0.03	−1.01***	−0.56**	0.13	0.01	0.24*	−1.12***
	(0.10)	(0.24)	(0.00)	(0.06)	(0.12)	(0.13)	(0.21)	(0.00)	(0.12)	(0.10)
R^2	0.20	0.39	/	0.45	0.84	0.34	0.35	/	0.40	0.85
Average VIF	1.83	1.83	1.83	1.83	1.83	1.19	1.19	1.19	1.19	1.19
Breusch–Pagan	0.00	0.00	0.08	0.00	0.00	0.02	0.00	0.07	0.00	0.00
Wooldridge test	0.32	0.49	0.37	0.33	0.20	0.12	0.12	0.15	0.11	0.15
AIC	−261.06	−148.08	−1786.13	−717.99	−412.85	−291.85	−179.57	−1733.11	−669.75	−525.01
Observations	247	247	247	247	247	247	247	247	247	247

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors are shown in parentheses. AIC, Akaike information criterion; VIF, variance inflation factor.

resource utilisation indices. The results suggest that the adverse effects of high population concentration are lessened by spreading the population more evenly across multiple centres. Although the negative impact of *POLY_F* is contrary to our expectations, it can be explained by the fact that as cities collaborate more on patents and innovations, economic activities typically increase, leading to higher pollution levels and water usage.

- Reducing environmental stress (RE): both morphological and functional polycentricity are positively associated with the RE index. The positive impact of *POLY_M* on RE may share the same rationale as its impact on ES. However, the difference between the positive impact of *POLY_F* on reducing RE and the negative impact on ES is notable. Despite intensified economic and industrial activities (represented by functional polycentric development) leading to higher pollution levels and water usage under the ES dimension, collaboration often extends to environmental management practices and green technologies. This collaboration may result in improved preservation of forests and higher energy consumption efficiency.
- Reducing human vulnerability (HV): there is no significant impact overall, although the regression coefficient of *POLY_F* is significant at the 10% level. However, the low R^2 value suggests limited explanatory power for this model, which is likely due to the low variance of this variable, as the proportion of area and deaths affected by natural disasters to total urban area is relatively small.
- Institutional capacity (IC): morphological polycentricity negatively impacts IC, while functional polycentricity shows no significant impact. This suggests that more centralised urban structures retain greater political power for managing environmental challenges effectively.
- Public stewardship (PS): while morphological polycentricity shows no significant impact, functional polycentricity is negatively associated with PS. The results suggest that the interconnectedness within functional PURs allows for more effective dissemination of information about environmental sustainability. This, in turn, promotes civic participation in environmental initiatives, contributing to higher levels of PS (Table 3).

4.2.3. Robustness test

A potential identification issue in our analysis is endogeneity resulting from reverse causality. Specifically, URs with better environmental conditions might attract more economic activities, leading to a more polycentric structure as businesses and people spread out to take advantage of the cleaner environment and better quality of life. We adopt instrumental variable (IV) regressions to deal with this issue. IVs must fulfil two conditions: they should be relevant (not weak) and valid (exogenous). If these two conditions are satisfied, FE regression modelling should be preferred over the IV estimation. We design different IVs for morphological and functional polycentricity: geographical constraints-predicted polycentricity for morphological polycentricity and the number of post offices per million people in cities in 1984 for functional polycentricity. The results confirm our main finding from the baseline model, and the endogeneity test results suggest that endogeneity is not a concern in our specifications (for detailed IV explanations and regression results, see Appendix E in the supplemental data online).

Besides, the environmental impact of polycentricity may differ based on the specific analytical and operational approaches used. To ensure the robustness of our results, we adopt three additional indicators, for both morphological and functional polycentricity. Besides, we analysed the effects across different administrative levels by conducting a sample analysis on URs. The overall results confirm the robustness of our primary conclusions, which are detailed in Appendices E–G online.

5. DISCUSSION AND CONCLUSIONS

PURs consisting of several nearby and interacting cities are often hypothesised to limit environmentally unsustainable concentrations, typical of large monocentric URs. While a growing body of research is developing explanations for these dynamics, there is little evidence regarding these effects' extent, conditions and duration. Against this background, this paper contributes to the literature by systematically investigating the environmental impact of polycentric urban development. Focusing on the case of URs in China, our theory and methodology build explicitly on and combine elements of recent studies that have pushed the debate forward: Qiang et al. (2023), who applied the environmental Kuznets curve theory to explain the trade-off between environmental pollution and urban structure development; Sha et al. (2020), Zheng et al. (2023) and Veneri (2010), who linked specific environment indicators and morphological dimension of polycentricity; and Esty et al. (2005) and Wolf et al. (2022), who developed environmental sustainability evaluation indexes at the global level.

Our research contributes to the literature in two ways. First, it conceptualises the evolutionary nature of PURs by positioning urban polycentricity within the urban resilience framework, highlighting how these regions adapt and reorganise over time in response to environmental and socio-economic changes. This dynamic perspective moves beyond existing studies' static, single environmental-dimensional analyses. Second, the study links a regional environmental sustainability index to both the morphological and functional dimensions of polycentricity. By integrating the tangible aspects of territorial development (i.e., physical population distribution) with the intangible aspects of relational dynamics (i.e., knowledge sharing), we provide a nuanced understanding of how these aspects interact to shape the environmental outcomes of PURs. Our reflections on the research design and key findings are summarised as follows.

5.1. Environmental sustainability assessment: a regional approach

Our discussion began with constructing the RESI, one of China's few benchmarking frameworks for cross-regional comparison. While Tao et al. (2019) have previously developed such a framework, most existing studies are more limited in scope. For instance, some focus exclusively on a few developed URs (Wang et al., 2022b), others operate at different spatial scales, such as provinces or cities (Wang et al., 2022a; Yu & Wen, 2010), and some address urban sustainability at large with environmental sustainability being but one of the components (Liang et al., 2022). Drawing on Esty et al.'s (2005) global index, we have selected indicators that are more sensitive to the regional scale. For example, instead of using the national index of threatened bird species, we adopt an urban-level biodiversity index derived from Landsat surface reflectance data, which can better reflect regional differences in biodiversity. Additionally, our index includes an innovative measure: the frequency of the keyword 'environmental sustainability' on the Baidu search engine. This is conceptually analogous to Esty et al.'s 'number of memberships in environmental intergovernmental organisations' but adapted to the Chinese context. Nonetheless, our index has limitations, particularly concerning the HV dimension, which shows little variation across URs. Consequently, this index has a much smaller entropy (5%) than other dimensions. As a result, our models have difficulties capturing meaningful patterns regarding how morphological or functional polycentricity impacts human vulnerability to natural disasters. Nevertheless, the overall significant impacts suggest that RESI has the potential for a precise and integrated analysis of regional environmental sustainability, which fulfils the need for the practical evaluation of polycentric development policies.

5.2. Urban resilience theory: an alternative theoretical basis

Another contribution of this paper is to offer an alternative theoretical framework to explain and disentangle the impact of polycentric development on environmental sustainability. We adapt urban resilience theory by drawing on the spatial dynamics in polycentric urban systems. Unlike the externalities theory used in previous studies, urban resilience adopts a systems-thinking approach that integrates multiple environmental goals, providing a more holistic perspective on the outcomes of polycentric development. While urban resilience has traditionally been quantified (e.g., Ribeiro & Gonçalves, 2019), this study refrains from doing so due to its conceptual overlap with environmental sustainability. As argued by Davidson et al. (2019), sustainability can be a component of resilience, and resilience is an element of sustainability. In this research, however, we distinguish between the two: environmental sustainability represents a normative vision for future regional development, whereas urban resilience is a functional attribute observed at varying levels of urban systems. This distinction underscores our use of resilience's six key attributes to theorise the environmental implications of polycentric development. Moreover, we would like to highlight that urban resilience is not an inherent characteristic of PURs. A region with evenly distributed populations or robust intercity networks does not automatically exhibit resilience. Instead, resilience emerges from the coordination and interaction of infrastructure, governance, social networks, and economic actors. These complex interdependencies underscore the need for strategic planning to enable PURs to adapt to and address challenges effectively.

5.3. Morphological polycentricity: positive impact on RESI

The often-hypothesised positive impact of morphological polycentricity on regional environmental sustainability in China was examined. Specifically, morphological polycentricity positively affects the overall RESI, as well as the sub-dimensions of ES and RE. ES reflects the state of natural and environmental systems, while RE evaluates the pressure exerted on environmental systems due to resource utilisation. The underlying reason for these positive impacts can be attributed to two urban resilience-based attributes: *redundancy* and *critical mass*. Redundancy ensures that multiple centres can provide similar functions, reducing the risk that a problem in one centre will disrupt the entire system. In connection with ES, this redundancy suggests that a decentralised urban structure tends to distribute pollution sources more evenly, preventing the overconcentration of pollutants in a single urban centre and improving air and water quality. Critical mass refers to the concentration of sufficient resources and activities within multiple centres to effectively sustain economic and social functions. When linked with RE, this attribute allows PURs to promote more efficient energy consumption and reduce waste pressure.

5.4. Functional polycentricity: contradictory effects among sub-dimensions of RESI

We expected functional polycentricity to be linked with higher RESI scores but found the opposite. However, this does not invalidate the overall impact of functional polycentricity. Upon closer inspection of the RESI sub-dimensions, we found that functional polycentric development has contradictory effects. While it generates negative impacts on ES and IC, it positively affects RE and PS. Three attributes of urban resilience – *diversity*, *flexibility* and *social cohesion* – can explain the positive impacts. It is important to note that we use patent cooperation data to describe functional polycentricity, and the benefits of the three attributes are also intangible. Diversity ensures a rich pool of ideas and resources, which enhances resource use efficiency and reduces environmental stress. Flexibility, facilitated by intercity cooperation, allows for rapid adaptation to environmental stress. Social cohesion fosters a collective approach to tackling environmental and public

challenges. In contrast, the negative impacts on ES and IC suggest that functional polycentricity may also introduce inefficiencies. The negative effect on ES indicated increased emissions could result from more dispersed activities. In contrast, the negative impact on PS suggests a fragmented governance structure that may hinder effective environmental management.

5.5. Interaction between different dimensions of polycentricity: complexity in urban systems

We hypothesised that the interaction between morphological and functional polycentricity would positively impact RESI. However, our findings reject this hypothesis, indicating that a combination of morphological polycentricity and functional monocentricity is positively related to RESI. In other words, urban systems, combining distributed population centres and centralised innovation hubs, are the 'ideal' settings for environmental sustainability. This reveals the *complex* nature of urban systems in China. As highlighted above, most URs in China tend to be more morphologically polycentric than functionally polycentric, lacking strong functional integration. Concentrated innovation hubs can optimise resource utilisation through centralised management compared with a more functionally polycentric urban setting. Meanwhile, morphological polycentricity reduces the strain on any single urban area, alleviating environmental stress related to high population density. This finding aligns with our observation that morphological polycentricity is solely negatively linked to IC among the five subdimensions. Morphological polycentricity often goes hand in hand with fragmented governance structures in China, where jurisdictions and administrative boundaries impede regional and collective institutional responses to environmental challenges.

5.6. Implications, limitations and avenues for further research

We conclude by reflecting on the normative presupposition regarding the environmental advantages of polycentric development. Environmental sustainability is a broad concept, similar to other policy goals attributed to polycentricity, such as territorial cohesion or economic efficiency. Proposals favouring polycentricity often fail to clarify the specific environmental dimension, treating polycentricity as an undifferentiated goal. However, our findings indicate trade-offs in the different aspects of environmental outcomes. For instance, polycentric structures benefit energy conservation but less for institutional capacity. This leads us to revisit Vandermotten et al.'s (2008, p. 1214) question: 'How can so many objectives be combined without raising any contradictions?' In this context, a key analytical and normative issue is to develop further what the policy objective' environmental sustainability' truly means and to determine which aspect should be prioritised when inconsistencies within sub-environmental goals are evident.

Several extensions of our work can be made from both theoretical and empirical dimensions. First, our research focuses solely on the urban resilience at the regional scale. However, urban resilience is scalable: factors contributing to urban resilience, such as green infrastructures, transport networks and social services, function differently depending on the scale on which they operate. For example, green infrastructures serve local communities by providing recreational space, while regional green belts connect multiple cities and support biodiversity on a larger scale. In other words, urban resilience at the regional level both influences and is influenced by resilience factors at the intra-city scale. Therefore, a potential extension of our work is incorporating cross-scale interactions in our theoretical framework.

Second, our analytical framework was designed to be applied to URs in China, using grided population datasets and patent cooperation data to proxy polycentricity. These data can, in principle, be obtained for all URs worldwide. However, this is less applicable to RESI, where significant differences in territorial scales of URs (e.g., URs in China are approximately 50 times larger than those in Europe in land cover) necessitate different considerations of RESI. For instance, in the EU context, RESI should be evaluated on a more granular scale based on finer indicators, such as 'net greenhouse gas emissions of the land use, land use change and forestry' in the domain of 'climate action' adopted in the Eurostat's sustainable development indicators.

Moreover, differences in the morphological and functional composition of regional urban systems further complicate the transferability of our results. For example, regions such as the Dutch Randstad and the German Rhine–Ruhr – characterised by more evenly distributed intercity networks of knowledge-based industries and innovation activities (Volgmann & Münter, 2018) – differ markedly from the hierarchical patterns of knowledge cooperation in China's YRD. Such differences are further shaped by variations in governance frameworks, which will influence the dynamics of polycentricity and its relationship with environmental outcomes. Therefore, while our findings offer new insights into URs across China, their applicability to other contexts must be interpreted cautiously.

Third, using patent cooperation data, our method for depicting functional polycentricity does not directly measure physical exchanges or concrete interactions between cities, which may seem only indirectly linked to RESI. However, its value lies in providing insights into intercity relationships' cognitive or symbolic aspects within URs. This aspect, though intangible, is crucial for a comprehensive understanding of the complexities inherent in city relationships. A pertinent question, then, is whether this intangible design is consistent with more tangible functional measures, such as human migration data, and whether the environmental implications observed in this research can be reproduced.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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NOTES

1. Using 40 indicators, the Environmental Performance Index ranks 180 countries on their progress toward improving environmental health, protecting ecosystem vitality and mitigating climate change (Wolf et al., 2022).
2. Urban impervious surface refers to the artificial surface cover on which water cannot infiltrate directly into the soil, including types of buildings, roads, squares, etc.
3. Assessment methods for environmental sustainability generally fall into three categories: 'environmental in general' method, life cycle assessment method and integrated indicator assessment method. Our focus narrows to the indicator method as it combines a broader spectrum of sustainability aspects compared with the others.
4. For the variable functional polycentricity (*POLY_F*), we use the log (X + 1) transformation in our regressions. This method handles cases where some URs had no patent cooperation in the early years of our study period, resulting in a functional polycentricity degree of 0, which cannot be directly log-transformed.

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