Applied Geography 171 (2024) 103368

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Towards a more compact urban form: A spatial-temporal study on the multi-dimensional compactness index of urban form in China

Xiaoxu Xing [a,1], Weihao Shi [b,1], Xiwei Wu [c], Yang Liu [a], Xiaoxi Wang [d], Yaojun Zhang [a,*]

[a] School of Applied Economics, Renmin University of China, Hai Dian District, No. 59 Zhongguancun Street, Beijing, 100872, China
[b] School of Architecture, Tianjin University, No.92, Weijin Road, Nankai District, Tianjin, 300072, China
[c] School of Population and Health, Renmin University of China, Hai Dian District, No. 59 Zhongguancun Street, Beijing, 100872, China
[d] School of Marxism, Putian University, No. 1133, Xueyuan Road, Chengxiang District, Putian, 351100, China

ARTICLE INFO

Handling Editor: Dr. Y.D. Wei

Keywords:
Urban form compactness index
GWPCA
Spatial-temporal evolution
Driving factors

ABSTRACT

Compact urban forms are essential for sustainable development, while few studies developed multidimensional urban form compactness index at the national scale from the perspective of spatial-temporal data, limiting our understanding of urban compactness mechanisms. In this study, a multidimensional urban form compactness index was created for 296 cities in China, focusing on spatial topology, morphology, and dynamics, addressing a gap in national-scale analyses from spatial-temporal viewpoints. Key findings include: (i) In the last two decades, significant alterations have occurred in urban compactness, with cities witnessing enhancements from 2005 to 2020. There's a spatial evolution trend characterized by higher compactness in the southeast and lower in the northwest, advancing from northwest to southeast. (ii) Urban expansion elements generally undermine urban compactness, whereas agglomeration efficiency elements contribute positively. (iii) Over time, while urban expansion impacts have shown relative stability over the years, agglomeration efficiency indicators have undergone an N-shaped fluctuation. Spatially, factors associated with urban sprawl enhance compactness in western and northeastern China, while land use factors are particularly effective in the northeastern, western, and northern areas. The study emphasizes the importance of using multidimensional composite indicators for thorough understanding of urban form compactness, offering significant insights for future policy and urban management.

1. Introduction

Over the past few decades, global cities, notably in China over the last 20 years, have witnessed significant urban expansion and urbanization (He & Zhou, 2024). The urban sprawl has led to the destruction of natural ecosystems and various environmental challenges, hindering sustainable urban development (Gong et al., 2012; Hou et al., 2023; Yuan et al., 2018). In response to smart urban growth, the concept of "compact cities" was first introduced in 1973 (Dantzig & Saaty, 1973), and since then researchers have been focusing on the relationship between compact development and urban sustainability (Chen et al., 2008; Co-operation O. f. E. Development, 2012; Wang, Wang, et al., 2019; Xia et al., 2020). Empirical research indicates that the compact city is increasingly recognized as a viable solution to various global sustainability challenges. Specifically, the compact urban form help reduces the reliance on fossil fuels and improve environmental quality (Xiaoxu et al., 2024), and enhance human well-being (Jiuwen et al., 2024). While the benefits of compact cities have been well articulated, the metrics of compact cities and the factors influencing the compactness of urban form are not sufficiently discussed. "Are cities compact and how can they become more compact?" is the basis for governments to achieve smart growth.

Initially, research on compact cities focused on developed countries, but in recent years, there has been a shift towards developing countries. Urban growth in developing countries has become a significant driving force of global urbanization (Cohen, 2004). As the largest developing country, China's urbanization rate is expected to exceed 80% by 2030 (Wu et al., 2016). However, due to China's state-owned land system, its

* Corresponding author.
E-mail addresses: xingxiaoxu@ruc.edu.cn, xingxiaoxu@pku.edu.cn (X. Xing), weihaoshi@tju.edu.cn (W. Shi), wuxiwei@ruc.edu.cn (X. Wu), liuyang_lois@163.com (Y. Liu), wangxx2022@ptu.edu.cn (X. Wang), zhyaojun@ruc.edu.cn (Y. Zhang).

[1] These authors contribute equally.

https://doi.org/10.1016/j.apgeog.2024.103368
Received 8 April 2024; Received in revised form 2 August 2024; Accepted 2 August 2024
Available online 9 August 2024

urban expansion since the reform and opening-up has been rapid but highly uneven (He & Zhou, 2024), leading to problems such as land resource wastage and ecological degradation. With the introduction of new urbanization in China, urban planning is encouraged to shape compact urban forms while adapting to economic growth. Some studies suggest that there are significant differences in urban compactness between developing countries like China and Western countries due to differences in economic structure and population density (He & Zhou, 2024). Therefore, due to China's rapid urbanization, unique planning layouts, and vast territory, it provides a comprehensive sample for the study of compact cities. The study of compact city forms in China is not only a necessary means to address its current issues of urban expansion but also an important reference for cities in developing countries worldwide to achieve sustainable development.

Urban form refers to the integrated physical composition of a city and the spatial structure manifested by various activities (Abrantes et al., 2017). As a geographical element of cities, the qualitative and quantitative study of urban form has long been a topic of interest in geography(Reis et al., 2016; Yi et al., 2016). Our study focuses on the compactness of urban form at a macro level. As a concept opposed to urban sprawl, compact cities emphasize the aggregation of overall form and internal connectivity. Currently, researchers employ various metrics to quantify compact cities, yet the comparability of compactness across different cities is poor and fails to comprehensively assess the compact characteristics of urban form. It requires a rigorous and consistent approach to the definition and measurement of urban form compactness attributes (Ahern, 2013). It is essential to recognize that the compactness of urban form is multi-dimensional. On one hand, compact form covering various aspects such as clustered internally and connected externally (Angel et al., 2020). This implies that relying solely on single landscape indicators for urban form is insufficient. On the other hand, differences in urban development stages and spatial growth processes lead to variations in urban form, resulting in different cities having preferences for specific indicators and weights regarding compactness. The characteristic has engendered a pressing urge among researchers to assess the multidimensional aspects of urban form (Zhou et al., 2019).

To address the aforementioned issues, we conduct a quantitative study on the dynamic evolution and driving mechanisms of urban form compactness in a sample of 296 Chinese cities. The primary objectives of this research are twofold: first, to comprehensively identify indicators for measuring urban form compactness and construct an index to assess the compactness of the urban forms of the Chinese city samples from a multidimensional spatiotemporal perspective; second, to explore the potential factors driving compact urban form and their spatiotemporal differentiation characteristics.

2. Literature review

2.1. Research on compact cities from a global and Chinese perspective

In 1973, the concept of "compact city" was introduced, defined as a city that makes efficient use of land space. They argued for the development of compact cities to curb the excessive sprawl of contemporary urban areas, protect limited natural resources, and maintain regional ecological balance (Dantzig & Saaty, 1973). This concept aligns with spatial structure theory, which examines the arrangement of activities across space and its implications for economic and social interactions (Bourne, 1982). Additionally, the compact city theorization suggests such urban forms can enhance sustainability by minimizing travel distances and promoting more efficient public service (Newman, 1987). In 1990, the European Community Commission published the "Green Paper on Urban Environment", promoting the compact city as a sustainable urban form, highlighting that a compact city emphasizes high density, mixed land use.

Since its introduction, the concept of compact cities has attracted significant attention in Western developed countries. Research has focused on three main areas: the theory and design methods of compact cities, urban compactness evaluation, and the benefits of compact cities. Theoretical research defines what constitutes a compact city and explores how to achieve compact urban development through transportation, land use, and public policy (Jabareen, 2006). This has led to practical applications like Tokyo's Transit-Oriented Development (TOD) and the urban growth boundary policies in the United States (Kirby et al., 2023). Evaluating urban compactness is key to transforming the concept into quantitative models and studies have used various indicators to assess compactness (Chakraborty et al., 2024). Benefit analysis focuses on the advantages of compact cities, such as reduced resource consumption, lower ecological impact, and improved well-being, providing insights for effective implementation.

China, experiencing rapid urbanization, has struggled to control urban sprawl, making it a new focus for compact city research (Luo et al., 2018). Existing research demonstrates that compact urban development strategies in China can enhance enterprise innovation on the production side (Wang et al., 2021), improve residents' welfare on the living side (Xia et al., 2022), and reduce greenhouse gas emissions on the ecological side (Shi et al., 2023). Under new urbanization and ecological initiatives, compact urban forms are advocated, yet there is no unified definition (Angel et al., 2020). Constructing a multidimensional compactness index can guide urban control in China and other developing countries.

2.2. Metrics of urban compactness

The concept of urban compactness, traditionally associated with high population density and urban development, is initially assessed from density, mixed-use, and intensity perspectives. Traditionally, a compact city is defined by its high population density, economic activity, or urban development. Density metrics often use the ratio of built-up area to city area, population density within built-up areas, or density of residential development within these areas (Kotharkar & Bahadure, 2020). Burton (2002)first proposed a comprehensive indicator system for measuring urban compactness, evaluating it from three perspectives: high-density cities, mixed-use cities, and intensified cities. Since then, numerous studies have proposed indices to define urban sprawl based on indicators from morphological, functional, and economic perspectives (Jia et al., 2022).

While the overall compactness is important, the multidimensional characteristics of urban form should not be overlooked, especially the urban footprints provided by satellite imagery (Angel et al., 2020). Current research on this topic does not yet provide a comprehensive understanding. On one hand, planar form is a primary indicator of urban expansion, effectively controlling urban sprawl and significantly optimizing environmental benefits. On the other hand, existing studies on compactness primarily focus on overall compactness indicators, causing urban form compactness to receive insufficient attention. The rise of diverse data in recent years offers a strong foundation, as urban form compactness is a multidimensional concept that must be examined from various perspectives.

In the field of urban form, three main indicators have been established to assess compactness, encompassing spatial urban contour characteristics, topology, and urban form dynamics. A method for measuring urban form compactness initially utilized the ratio of built-up area to the major axis, leading to the development of additional compactness measures such as the circumcircle of the city and other contour-based metric (Thinh et al., 2002). Additionally, a spatial form-based metric was developed to analyze urban spatial form diversity and complexity, with studies examining local spatial characteristics and landscape pattern features from the perspective of urban contour (Kaza, 2022; Mariaflavia, 2020). While for topology, Liu and Tian (2022) introduced a metric grounded in spatial topology to evaluate urban form complexity, focusing on the topology of urban networks, including node counts, connections, and node degree distributions (Baruah et al., 2021). Finally, the researchers propose a method based on spatial dynamics to assess the evolution of urban spatial form. Many studies concentrate on the temporal shifts in urban forms, encompassing growth, contraction, and structural alteration (Miguel et al., 2016).

However, existing evaluations of urban form compactness focus on measuring the overall contour characteristics of the city exterior, neglecting the spatial relationships between patches in polycentric urban development model and the dynamic characteristics of urban form changes. Moreover, urban compactness indicators are often applied as multiple single metrics within specific cases (Kotharkar et al., 2014), which can lead to the awkward situation where each city appears to have a high compactness indicator, reducing comparability. Therefore, a more comprehensive and integrated approach should be developed to yield more accurate and realistic results.

To construct a composite index, excluding correlated indicators and selecting the most representative ones is essential. Some studies have explored methods for integrating multidimensional compactness indicators. Initially, Schwarz (2010) used correlation and factor analysis to identify minimal indicator sets for urban morphology. Later, studies combined urban function and human activity indicators into a functional compactness index (Lan et al., 2021). Ding et al. (2022) utilized the Principal Component Analysis (PCA) method to integrate several landscape indexes for evaluating the urban form characteristics of Chinese counties. These studies provide valuable insights but overlook the spatial heterogeneity of urban form in China. A comprehensive evaluation of the compactness and driving mechanisms of urban form from a spatiotemporal heterogeneity perspective will facilitate the analysis of urban development and the implementation of new urbanization strategies.

2.3. Factors influencing compact cities

The compact form of a city is a representation of the evolution of its spatial structure, which is influenced by development, change, government and internal dimensions (Dadashpoor & Malekzadeh, 2020). According to Dadashpoor and Malekzadeh (2020), we summarize the indicators that affect urban compactness into three categories: urban expansion, agglomeration efficiency and urban spatial planning.

The predominant factor influencing urban compactness is the rapid population expansion during urbanization (Zhang et al., 2019). In the central area, as the population increasingly congregates in cities, construction land expands accordingly. This urbanization intensifies the tension between population and land availability, resulting in the city's sporadic expansion towards its periphery (Wang et al., 2019), reducing the compactness of suburban regions surrounding cities.

While population growth acts as a principal driver for urban dispersion, urban agglomeration efficiency remains the paramount centripetal factor for compact urban development. Improved urban transport systems boost city accessibility and connectivity, with changes in spatial accessibility shaping the magnitude and orientation of urban structures.Meanwhile, the decentralization of industrial layouts results in traditional industries extending into the suburbs, propelling a significant shift of manufacturing employment to suburban areas, facilitating population redistribution and urban sprawl (Acheampong et al., 2016). Additionally, investments in essential urban infrastructure further advance compact urban development (Liu et al., 2019).

Furthermore, both land use changes and topography significantly influence urban sprawl and consequently urban compactness (Garcia Manzato & Rodrigues da Silva, 2009). Strategic land planning minimizes urban space wastage, conserves construction land, and refines city spatial structure, fostering a more compact, eco-friendly, and habitable urban environment (He et al., 2020). Topographical variations play a role in urban compactness as well (Angel et al., 2020). Steeper terrains restrict urban sprawl, leading to centralized urban patterns. Conversely, second-tier cities with flatter landscapes tend to exhibit higher urban land densities at their peripheries (Shukla et al., 2021).

2.4. Literature summary

Based on previous research, a compact urban form should exhibit characteristics such as proximity and cohesion, with an emphasis on being as circular as possible (Angel et al., 2010). However, focusing solely on overall compactness may overlook crucial aspects such as internal connectivity and the dynamic characteristics of urban form. To address this, we have expanded our theoretical framework to incorporate three key dimensions: *Spatial Contour, Spatial Topology, and Spatial Dynamics*, each corresponding to specific theoretical foundations. As shown in Fig. 1, Sp*atial Contour* is grounded in urban morphology theory, which focuses on the physical form and structure of cities, including their boundaries, shapes, and layouts (Kropf, 2009). *Spatial Topology* is based on spatial structure theory, a method for analyzing spatial configurations and understanding how spatial elements are interconnected and accessible (Dhanani et al., 2017). This theory studies the topological relationships within urban spaces, examining how the layout of streets and public spaces affects movement, interaction, and accessibility. *Spatial Dynamics* draws from evolutionary geography theory, which analyzes how urban systems evolve over time and focuses on the temporal changes in urban form and function, including urban expansion, land-use changes, and population migration (Scheuer et al., 2016). By integrating these theories, our expanded theoretical framework not only addresses the physical and structural aspects of urban form but also incorporates the dynamic processes that influence urban compactness over time. This comprehensive approach allows us to more accurately assess the multi-dimensional nature of urban compactness and provides a robust foundation for analyzing the complexities of urban form in Chinese cities.

To operationalize our theoretical framework, we developed the "Urban Form Compactness Index," which integrates multiple dimensional indicators to establish a comprehensive and replicable benchmark for urban compactness. The construction of this index follows these key steps: firstly, a compact urban form should have characteristics such as proximity and cohesion, with an emphasis on the shape being as circular as possible. *Spatial Contour* indicators, which can include metrics such as proximity measures, circularity ratio, and edge-to-area ratio. These metrics capture the geometric characteristics of urban form, emphasizing the compactness of the urban boundary and the efficiency of land use. Secondly, it is important to recognize that an excessive focus on achieving overall compactness can lead to the oversight of crucial aspects such as internal connectivity and dynamic characteristics of urban form. *Spatial Topology* indicators can involve metrics like the connectivity index, integration values, and network density. These metrics assess the internal connectivity of the urban form, evaluating how well different parts of the city are linked and how accessible they are. Finally, *Spatial Dynamics* indicators can comprise metrics such as the urban expansion footprint, growth rate, and landscape constraints, which evaluate the temporal dynamics of urban form, measuring how compact the urban form remains under the pressures of natural landscape constraints and urban growth. The integration of urban morphology theory, spatial structure theory, and evolutionary geography theory provides a robust theoretical foundation for our study. By constructing the "Urban Form Compactness Index" with specific dimensional indicators, we can comprehensively assess the compactness of urban forms in Chinese cities.

Based on previous research, we classified the factors affecting the compactness of urban form into three categories: urban expansion, agglomeration efficiency and land and topography. However, it is worth noting that although the mechanisms influencing compact urban form have garnered attention, they have not been thoroughly discussed. On one hand, few studies have fully considered all three types of influencing factors, limiting the comparison of their relative impacts. Moreover, the conclusions of existing studies are inconsistent, raising another issue: the

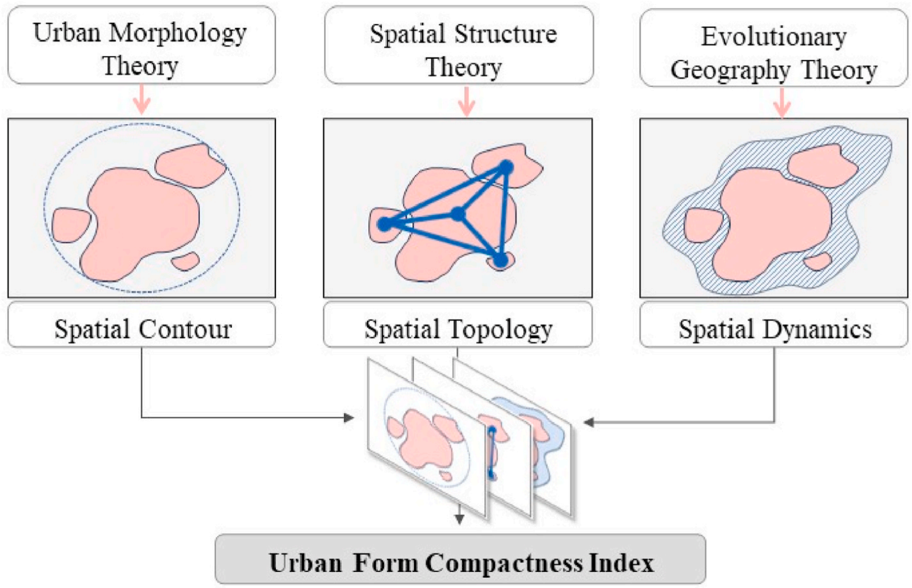


Fig. 1. Theoretical framework of urban form compactness index.

potential spatiotemporal heterogeneity of these influencing mechanisms, which is particularly crucial in the context of China's uneven urban development. To address this research gap, we will employ spatial econometrics and a spatiotemporal geographically weighted regression model to comprehensively explore the three mechanisms influencing urban form compactness from both overall and local perspectives.

3. Data and methodology

3.1. Research framework

We structured our study into four sequential steps. Initially, we constructed the Urban Form Compactness Index utilizing three remote sensing databases and the Geographically Weighted Principal Component Analysis (GWPCA) and subsequently analyzed its spatial-temporal evolution. Next, we assembled a database for the index's driving factors. Leveraging this, we employed the Spatial Durbin Model (SDM) and Geographically and Temporally Weighted Regression (GTWR) to investigate their overarching and heterogeneous driving mechanisms. Concludingly, we deliberated the findings and formulated pertinent policy suggestions. The encompassing study flow is depicted in Fig. 2.

3.2. Research area and data resource

To systematically analyze the spatiotemporal evolution of urban form compactness indices and their influencing mechanisms, this study selects prefecture-level and above cities in China as the research area. As the largest developing country, the implementation of compact city policies in China has garnered significant global attention. Under the dual constraints of economic and population scale, the prefecture-level city system in China is relatively complete, making it conducive for analyzing urban form compactness (He & Zhou, 2024). Additionally, prefecture-level cities are key units for controlling urban expansion in China, facilitating better policy implementation. We excluded cities with jurisdictional changes or missing data during the study period, resulting in a final dataset of 296 prefecture-level and above cities.

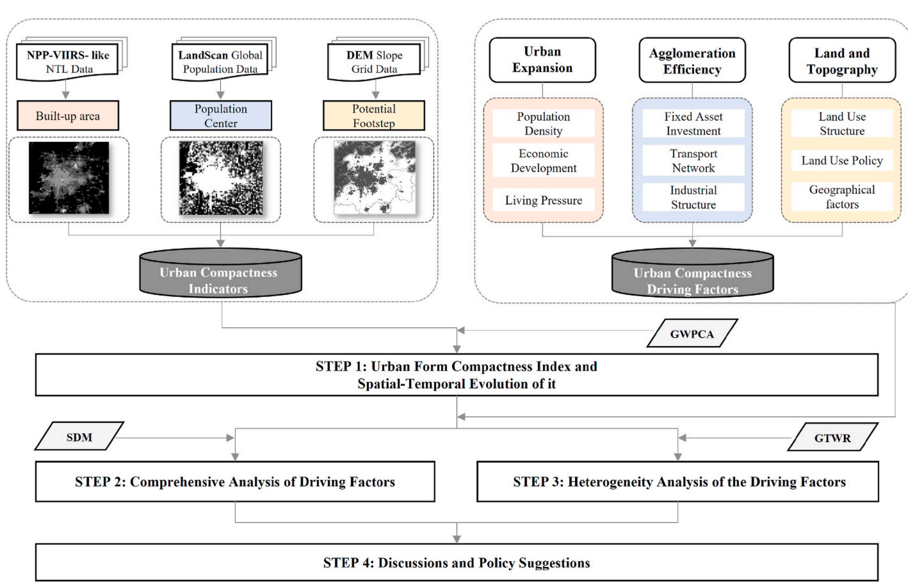


Fig. 2. Study workflow.

The urban compactness indicators are derived from three primary datasets: LandScan Global Population Data from the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL), NPP-VIIRS- like NTL Data from Harvard University Database and DEM Slope Grid Data adjusted by elevation corrections and suitability assessment. The drivers of compactness index are all from "China Urban Statistical Yearbook" and "China Urban Construction Statistical Yearbook".

3.3. Indicators of urban form compactness index

The data processing is based on the night-time lighting dataset, which identifies the extent of the built-up area of the city. Notably, these five indicators are inherent to the concept of compact urban form, which we did not define. However, we have innovated the meaning and calculation of each indicator. Specifically, we incorporated the degree of urban polycentricity into the evaluation of compactness. Identifying urban centers based on LandScan data has proven effective (Li & Ben, 2022; Liu & Wang, 2016), the specific steps and methods for center identification can be found in Appendix B. Thus *Close* indicator uses the distance from various center of population distribution on the basis of the built-up area. *Cohesion*, *Circle* and *Continuity* are calculated using the *cohesion*, *circle*, and *AI* metrics from the Fragstats 4.2 software, respectively, representing the aggregation of urban patches, the roundness of the city, and the connectivity of patches. The use of landscape patterns to measure urban form has been widely accepted (Chakraborty et al., 2024). The *Fullness* indicator is calculated by the proportion of the built-up area that can be developed during the sprawl process, which was define according to previous study (Angel et al., 2020; Xiaoxu et al., 2024). The detailed calculation process can be found in Appendix A. Taking the city of Beijing as an example, Fig. 3 shows the data processing and the calculation of the indicators. And the correlation between the variables and theoretical framework can be seen in Fig. 1. The variables are defined as shown in Table 1.

3.4. Drivers of the urban form compactness index

From the insights gleaned on the spatiotemporal evolution of urban spatial compactness, this section delves into the spatial externalities and temporal variability of urban compactness determinants. Based on literature, we pinpoint nine potential influencing factors spanning three domains: urban expansion, agglomeration efficiency, and land and topography (Dadashpoor & Malekzadeh, 2020). In terms of urban expansion, the formation of metropolises is often accompanied by high GDP per capita, urban living pressure and population density (Schneider & Woodcock, 2008). In terms of agglomeration efficiency, the formation of compact cities can be facilitated by an appropriate industrial agglomeration structure, efficient fixed asset investment and a well-developed urban transport system (Jiuwen et al., 2024; Kelobonye et al., 2019). As for land and topography, different land use policies, urban development planning policies and geographical forms may have different effects on urban compactness due to the different historical trends and positioning of cities (Bibri, 2020). The specific variable definitions and descriptive statistics are shown in Table 2 and the visualization of variable correlations can be found in Appendix C.

3.5. GWPCA for integrated urban compact indicators

Previous studies used spatial equilibrium weights to combine urban compact indicators, such as addition (Lan et al., 2021), entropy weight (Jia et al., 2022) and PCA (Ding et al., 2022). However, traditional assignment methods fail to meet the requirements of regional heterogeneity, as differences in the stages of urban development result in variations in the weightings of urban form indices among cities (Wu et al., 2023; Zhou et al., 2019).

Thereby, we employed the GWPCA to construct a composite urban compactness indicator from five basic indicators. GWPCA, a spatial statistical method, enhances ordinary PCA by incorporating a spatial

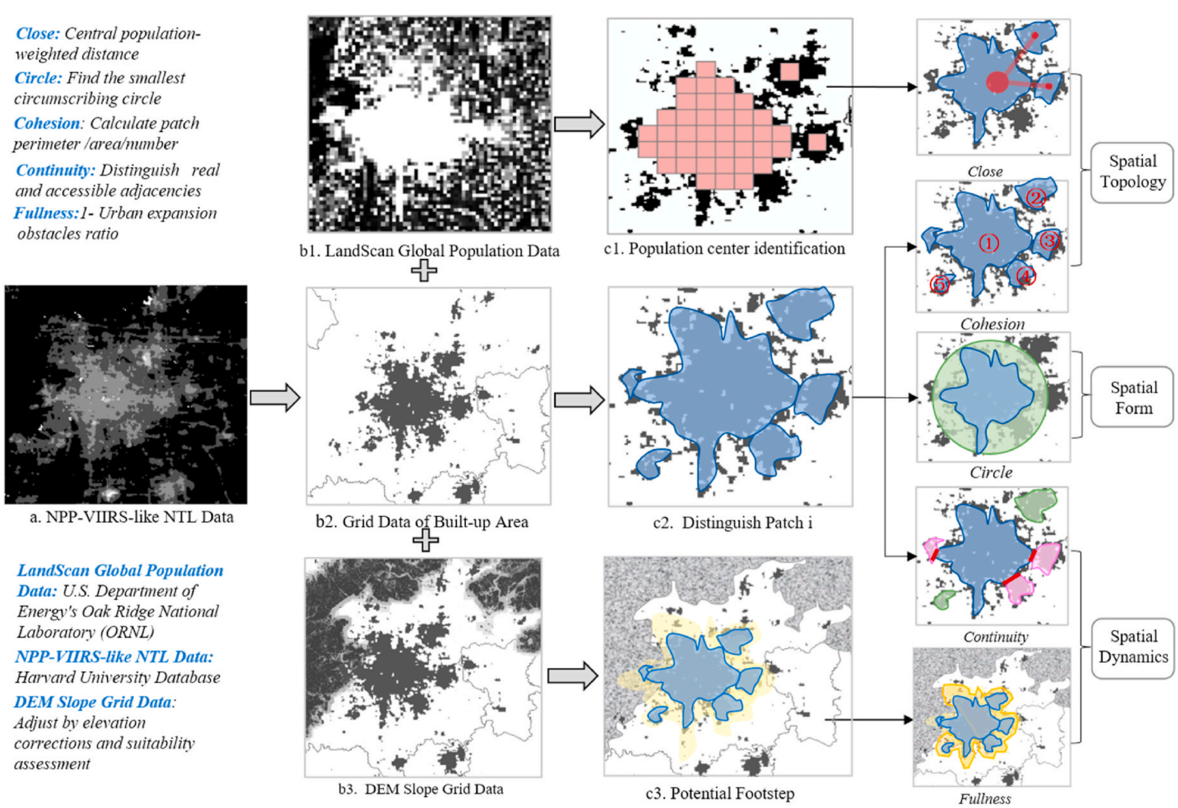


Fig. 3. Data Processing Flowchart of City Compactness Indicator (Take Beijing as an example). "+" means overlays of different remote sensing data, while "}" means indicators of the same type.

Table 1
Definition of compactness index.

Formula	Definition
$Close = \sqrt{\sum_{i=1}^{n} \frac{(I_i - \overline{I})^2}{n}} / \left(\frac{I_{max}}{2}\right)$; $I_i = x_i * d_i$; $I_{max} = x_{max} * d_{imax}$	n represents the number of identified centers, d_i is the distance from center i to other centers, and x_i is the population of center i. The larger the indicator, the more connected and less dispersed the city's population centers are
$Circle = \frac{A_i}{A_{circle\ i}} * \frac{A_i}{\sum_{i=1}^{n} A_i}$;	A_i of patch i.; $A_{circle\ i}$ area of smallest circumscribing circle around patch ij. 0< *Circle* <1 *Circle* approaches 1 for circular patches and approaches 0 for elongated, linear patches one cell wide.
$Cohesion = \left[1 - \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} P_i \sqrt{A_i}}\right]\left[1 - \frac{1}{\sqrt{n}}\right]^{-1}$;	P_i = perimeter of patch i in terms of number of cell surfaces. A_i = area of patch i in terms of number of Cells. n = total number of cells in the landscape. *Cohesion* approaches 0 as the proportion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected.
$Continuity = \frac{M_{real\ i}}{M_{access\ i}}$;	$M_{real\ i}$ = number of real neighboring patches of patch i. $M_{access\ i}$ = maximum number of like adjacencies (joins) between pixels of patch type i based on the single -count method. *Continuity* equals 0 when the focal patch type is maximally disaggregated; *Continuity* increases as the focal patch type is increasingly aggregated and equals 1 when the patch type is maximally aggregated into a single, compact patch.
$Fullness = \frac{A_{deve\ i}}{A_{buffer\ i}}$;	$A_{deve\ i}$ = area of developable land in buffer area. $A_{buffer\ i}$ = buffer area of 1000m around built-up area. When *Fullness* is higher, the higher the degree of freedom in the direction of urban sprawl, the forms are more likely to be more regular and compact.

Table 2
Definition and descriptive statistics of the variables influencing urban compactness.

Classification	Variables	Description	Mean	S.D.
Urban Expansion	*Agdp*	Gross national product per capita	0.288	0.248
	Livpre	Sales of commercial residential units/sales area of commercial residential units (billion yuan/sqm)/average annual wages of all employees	0.377	0.287
	Peoarea	Population density: resident population/built-up area	0.208	0.234
Agglomeration Efficiency	*Indus*	The Herfindahl-Hirschmann index, with a smaller index indicating weaker industrial agglomeration. $Indus_{c,t} = \sum_{i=1}^{N}\left(emp_{c,i,t}/emp_{c,t}\right)^2$ where c indicates city, i indicates industry, t indicates time period, $emp_{c,i,t}$ is the number of employment in city c industry i and time t.	0.259	0.245
	Invest	Total social fixed asset investment	0.261	0.288
	Roadper	Road area per capita	0.283	0.271
Land and Topography	*Elevat*	Average elevation	0.578	0.241
	Zone	Number of provincial and national development zones	0.349	0.228
	Landuse	Total area of industrial land, storage land and external transport land/built-up area	0.650	0.229

Variables are normalized and dimensionless.

weight matrix to account for spatial correlations. This approach enables the detection of spatial variations, facilitating a deeper understanding of spatial dynamics and effective spatial data analysis (Robinson et al., 2019). Mathematically, the geographically weighted variance-covariance matrix is calculated as equation (1), where $W_{(u,v)}$ is a diagonal matrix of geographical weights that are generated by the chosen kernel weighting function (Mishra, 2018). The geographically and temporally weighted principal components at spatiotemporal location (u_i, v_i) can be written as (2). The geographically and temporally weighted component scores at the spatiotemporal location $T_{(u_i,v_i)}$ are found by post-multiplying the original data X by geographically and temporally weighted eigenvector matrices $L_{(u_i,v_i)}$ (equation (3)) (Han et al., 2022). And finally index of *Urban Compactness* for each ward is the summation of the loadings for each variable in the first component and the value of the basic indicators for each ward (equation (4)). The spatial correlation of the indicators constructed based on this method is strong, with the Moran I coefficient values for 2005–2020 all above 0.9 and passing the 1% significance test (Appendix Figure C1).

$$\sum\nolimits_{(u,v)} = X^T W_{(u,v)} X \tag{1}$$

$$\sum\nolimits_{(u_i,v_i)} = LVL^T \Big| (u_i, v_i) \tag{2}$$

$$L_{(u_i,v_i)} = XL_{(u_i,v_i)} \tag{3}$$

$$GWPCA\ Compactness_i = a_{1i}Close_i + a_{2i}Cohesion_i + a_{3i}Circle_i + a_{4i}Continuity_i + a_{5i}Fullness_i \tag{4}$$

3.6. SDM and GTWR model

The presence of spatial factors may impair the accuracy of the estimated results of general panel regression models. Therefore, we constructed a spatial panel regression model for analysis, which can better test the relationship between variables and spatial effects. Based on the inverse distance matrix of Chinese prefecture-level cities, we built the spatial weight matrix. After Lagrange multiplier (LM) test and likelihood ratio (LR) test, we finally selected the spatial Durbin model (SDM). The spatial Durbin model considers both the influence of the dependent variable's and the independent variable's spatial lag term on the dependent variable into account, and is commonly used to examine the independent variable's geographical spillover impact (LeSage & Pace, 2009). Further through the Hausman test, the model finally determined in this paper is the space Durbin model of the individual time double fixed effect. The model is calculated as follows:

$$Y_{it} = \beta_0 + \rho \sum_{j=1}^{n} W_{ij}Y_{jt} + \theta X_{it} + \phi \sum_{j=1}^{n} W_{jt}X_{jt} + \alpha_i + \delta_t + \varepsilon_{it} \tag{5}$$

Among them, counties are represented by i and j, W_{ij} denotes the matrix, Y_{it} represents the explained variable, which is the urban form compactness index, and X_{it} is each explaining variable. θ is the explaining variable's regression coefficient without considering the spatial effect, ρ and ϕ are the geographic regression coefficient of the explained variable and explanatory variable, which are the dependent and independent variable's space spillover impact. α_i represents the county individual fixed effect, while δ_t stands for the time fixed effect, ε_{it} is the random disturbance term.

However, for spatial-temporal data, the SDM is unable to explore the heterogeneous characteristics of the impact mechanisms and effectively visualize the impact results for differential classification analysis. In order to quantify the spatial-temporal heterogeneity of impact mechanisms, the GTWR model was introduced, the core idea of which is to estimate the local regression by observing the adjacent sample data information, and using the spatial location as one of the regression parameters(Huang et al., 2010). As the spatial location changes, it also changes the estimation parameter, so that the temporal and spatial relationship between the dependent variable and its influencing factors can be reflected in the GTWR model. The basic form of the model is:

$$Y_i = \beta_0(\mu_i, \nu_i, t_i) + \sum_k \beta_k(\mu_i, \nu_i, t_i) X_{it} + \varepsilon_i \tag{6}$$

In the GTWR model, each sample point has a three-dimensional spatial-temporal coordinate (μ_i, ν_i, t_i), where t_i is the temporal distance, and the temporal and spatial parameters are combined with the spatial parameters by homogenization. For each regression point i and sample k, the regression coefficient between them is $\beta_k(\mu_i, \nu_i, t_i)$.

4. Results

4.1. Spatial-temporal evolution of urban form compactness index

Based on temporal analyze of urban compactness index in 2005–2020 (Fig. 4) and the index distribution in 2005, 2010, 2015 and 2020 (Fig. 5), the temporal and spatial evolution of compact cities were analyzed. The overall urban compactness in China during 2005–2020 shows steady upward trend and a spatial distribution pattern of "high in the south-east and low in the north-west", with an evolution spread from the north-western region to the south-eastern region.

Fig. 4 illustrates the progressive temporal trend of the Urban Compactness Index, delineated into four phases. From 2005 to 2011, there was marginal fluctuation in urban compactness, maintaining minimal disparities among cities. Subsequently, between 2011 and 2013, there was a marked augmentation in compactness, the median escalating from 24.9 to 31.8. Although the index fluctuated between 2014 and 2017, it remained relatively stable, then consistently increased from 2018 to 2020, reaching a median of 33.6 in 2020 and reducing disparities among cities. The notable rise in compactness from 2011 to 2013 is primarily attributed to rapid urbanization and government policies promoting dense urban development. The growth in compactness from 2018 to 2020 may reflect regulations on urban sprawl and possibly the indirect effects of COVID-19, which changed living patterns and limited urban expansion.

The evolution of urban compactness in Chinese cities between 2005 and 2020 provides insights into varying regional development trajectories and the outcomes of strategic planning across different stages (Fig. 5). (i) During the early development phase in 2005, urban compactness was generally low nationwide(He & Wu, 2007). Owing to historical industrial centralization, the majority of compact cities were concentrated in the Beijing-Tianjin-Hebei region and other traditional industrial areas in the north. In contrast, the southern regions, which were just beginning their expansion and were focused on developing extensive industrial and residential areas, exhibited lower levels of compactness. (ii) During the expansion and transformation phase in 2010, Northern regions continued to exhibit early patterns of urban compactness with minimal changes. This era marked the onset of declining economic dynamism in the north, in stark contrast to the continuous expansion in the south, where urban compactness in coastal cities began to show signs of increase (Gao et al., 2015). (iii) During the smart growth and renewal phase in 2015, urban compactness in southeastern cities notably enhanced. By emphasizing high-density living, mixed land use, and efficient public transportation, these cities significantly enhanced their compactness following the approval of the River Delta Regional Plan (Lu et al., 2018). (iv) By the Advanced Urban Compactness phase in 2020, the geographic center of urban compactness had distinctly shifted towards the southern provinces, reflecting their successful implementation of smart growth policies. This transition was largely influenced by demographic trends, including significant inflows (Luo et al., 2018).

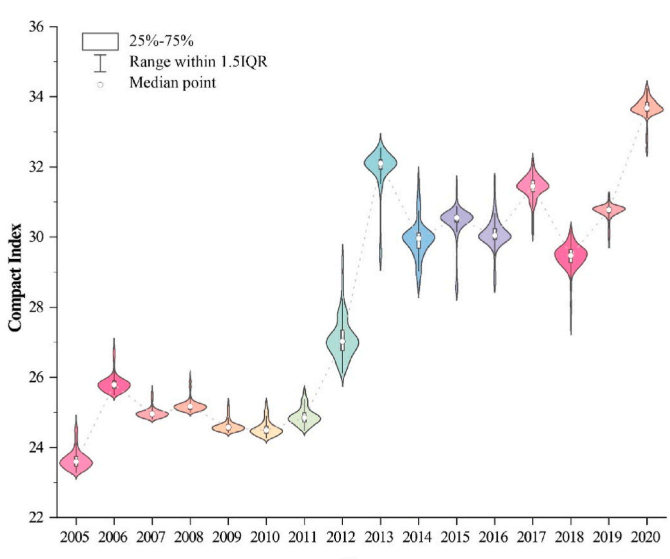


Fig. 4. The temporal trend of urban compactness index from 2005 to 2020.

To further elucidate the changes in urban compactness at different stages of city development, Appendix Figure C4 offers a comparative analysis focusing on the built-up areas of Mudanjiang City and Shenzhen City as of 2020 (Li et al., 2022; Ou et al., 2019). Urban compactness tends to decrease and then increase over the course of urban development such that cities at different stages of development may exhibit similar patterns of compact growth. Mudanjiang, which entered its development phase earlier, exhibits limited economic growth and urban expansion, resulting in smaller city block sizes and lower urban compactness. In stark contrast, Shenzhen is in the advanced stages of "Smart Growth," where extensive urban planning and sophisticated infrastructure layouts support a higher degree of urban compactness. This vivid contrast highlights the significant differences that can exist within regions classified as "compact cities," particularly in terms of regional development stages, economic conditions, and strategic urban planning. The analysis of regional and differentiated influencing factors plays a pivotal role in devising targeted urban planning strategies. The necessity to reflect these distinct regional requirements is the primary motivation for employing the GTWR model in subsequent analyses.

4.2. Comprehensive analysis of driving factors using the Spatial Durbin Model

According to Table 3, the analysis of the spatial Durbin model mainly includes the direct and indirect effects of urban expansion, agglomeration efficiency and land and topography on urban compactness. Overall, factors of agglomeration efficiency have the greatest impact on urban compactness, and the indirect effects of these factors outweigh the direct effects.

The spatial Durbin model revealed significant negative direct effects of economic development level, urban living pressure, and population density on urban compactness, as identified by Liu et al. (2020). Especially, the increase in *Livpre* deepens the tension and contradictions in urban infrastructure, public services and other aspects, which prompts the government to take measures to expand the urban scale, leading to the decentralization of the city and the decrease in urban compactness. The long-term indirect effects of the three sub-indicators are greater than their direct effects, and significant at a 5% level. An increase in a city's economic development level, urban life pressure, and population density can reduce the compactness of surrounding cities due to the suction effects of talent loss, increased competition, and resource attraction (Zhou & He, 2007).

The results revealed significant negative direct effects of agglomeration efficiency factors. During the process of urban development, a large amount of *Invest* can promote the construction of infrastructure

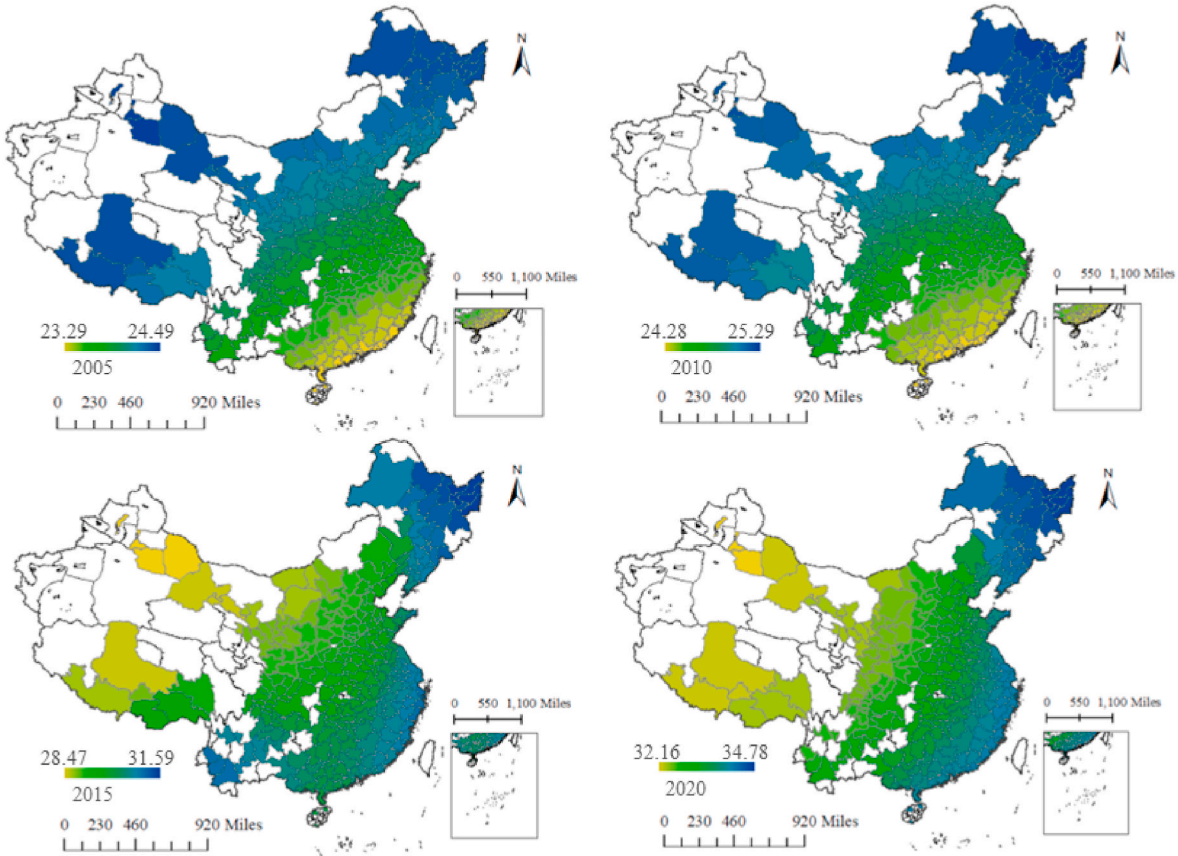


Fig. 5. Spatial distribution of urban compactness index in year 2005, 2010, 2015 and 2020.

Table 3
Regression results of a spatial Durbin model of factors influencing urban compactness.

Merge		LR_Direct		LR_Indirect		LR_Total	
		Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
Urban Expansion	*Agdp*	−0.006[a]	(-3.516)	−0.165[a]	(-3.650)	−0.170[a]	(-3.651)
	Livpre	−0.002[b]	(-2.045)	−0.061[b]	(-2.031)	−0.063[b]	(-2.035)
	Peoarea	−0.002[a]	(-2.624)	−0.105[a]	(-4.054)	−0.108[a]	(-4.014)
Agglomeration Efficiency	*Indus*	0.005[a]	(4.796)	0.155[a]	(4.772)	0.161[a]	(4.779)
	Invest	0.007[a]	(4.587)	0.201[a]	(4.377)	0.209[a]	(4.390)
	Roadper	0.003[a]	(2.722)	0.122[a]	(3.792)	0.125[a]	(3.759)
Land and Topography	*Elevat*	−0.001	(-0.853)	−0.022	(-1.244)	−0.023	(-1.241)
	Zone	0.000	(0.203)	0.034	(1.146)	0.034	(1.114)
	Landuse	0.001	(0.601)	0.014	(0.428)	0.014	(0.434)

[a] $p < 0.01$.
[b] $p < 0.05$.

and public service facilities within the city, such as transportation systems, residential areas, and public facilities, thereby improving the spatial efficiency of the city and making it more compact. The increase in *Roadper* can alleviate the traffic pressure in the city, reduce traffic congestion and accidents, and thus improve the compactness of the city. The indirect effect is significantly larger than the direct effect, indicating the positive externality of agglomeration efficiency factors, which can be attributed to the strengthen of connection in both industry, commercial, cultural, and social with surrounding cities (Zhang et al., 2022). These connections will further promote the urban construction of surrounding cities and thus promote the improvement of their compactness.

Regarding Land and Topography Factors, both the direct and indirect effects of these factors on urban compactness lack statistical significance. Their influence hinges on the city's geographical positioning and its historical development trajectory. For "*Elevat*", it's notable that cities located in mountainous regions at higher altitudes often encounter spatial limitations which hinder vertical development, resulting in a relatively dispersed urban form. However, the effect of altitude on urban compactness is inconsequential in areas with flat terrains. As for "*Zone*", there are two sides to consider. Firstly, development zones in China are typically positioned in less populated areas, either interstitially between cities or at their peripheries. Such zones frequently necessitate extensive land development and infrastructure projects, leading to more dispersed urban configurations (Li, Gao, et al., 2022). Conversely, these zones also bolster resource consolidation and sharing across regions, which can circumvent redundant constructions and resource wastage, potentially enhancing urban compactness (Yoon, 2020).

4.3. Heterogeneity analysis of the driving factors using GTWR model

4.3.1. Model construction and fitting results

The Moran's I index analysis showed a strong spatial effect of urban compactness. The GTWR model was analyzed based on the GTWR plugin in ArcGIS software. The obtained model R^2 is 0.98 and the descriptive statistics are shown in Table 4. The goodness of fit of GTWR and the non-stationarity of the spatial and temporal effects of each variable further confirm the applicability of the GTWR model.

The conclusions derived from both the median and mean values of variable strengths align with the results of the spatial Durbin model analysis. The median and mean values indicate that the indicators within the urban expansion category predominantly act as inhibitors. Conversely, indicators in the agglomeration efficiency category primarily promote urban compactness. Investments in industry, transportation, and construction all contribute to more compact and efficient urban environments. Instinctively, within the land and topography category, higher elevations correlate with less compact cities. However, the establishment of development zones and a greater percentage of industrial land within cities foster compactness. The positive and negative coefficients of *Invest* and *Elevat* are roughly equal, suggesting a lack of clear directionality within this spatiotemporal range. Further spatiotemporal descriptive analyses are needed.

4.3.2. Temporal evolution of the driving factors

Fig. 6 shows the coefficients' temporal evolution of the impact indicators on urban compactness from 2005 to 2020. Overall, the impact coefficients of urban expansion and land indicators are relatively stable over time, while the temporal stability of agglomeration efficiency indicators is weaker.

Fig. 6(a) indicates that cities with higher economic development levels tend to have lower urban compactness. This trend stems from the prevalent crude urban sprawl in China from 2005 to 2020, characterized by high-density population concentration in large cities, leading to inefficient sprawl (Schneider & Woodcock, 2008). However, in the 2010, *Agdp* boosted urban compactness, mainly due to the economic stimulus package released in 2008, centered on the 'four trillion' investment focusing on key infrastructure projects in economically disadvantaged areas, thus fostering rapid urban expansion in these regions (He et al., 2009). *Livpre* has moved from promoting and inhibiting initially to promoting across the board. During the period 2005–2020, impact zone of *Peoarea* on urban compactness gradually shrinks, yet globally, *Peoarea* still exerted a suppressive effect on compactness.

In terms of agglomeration efficiency factors. Combined with Fig. 6 (b), it can be seen that *Indus, Invest,* and *Roadper* all show a trend of initially positively promoting urban compactness but subsequently impede it. Specifically, the influence of *Indus* on compactness shifted negatively from 2005 to 2020, where early attempts to attract industrial agglomeration through extensive land use led to urban sprawl (Peng et al., 2017). The coefficient of *Invest* has gradually weakened, with its effect on compactness approaching 0. As for the effect of *Roadper*, some cities have adopted a 'big plan, big build' approach in order to attract investment, which has led to a significant increase in the total length and width of roads without a corresponding increase in population, resulting in an increase in road area per capita and a decrease in urban compactness (Zhou et al., 2022).

Concerning land and topography factors, as illustrated in Fig. 6(c), elevation consistently had little impact on urban compactness from 2005 to 2020, registering a value of 0. The influence of the *Zone* on urban compactness peaked in 2015, aligning with the release of China's "New-type Urbanization Plan (2014–2020)." This plan mandated advanced planning standards for development zones, emphasizing compact urban development (Chen et al., 2016). It required cities to judiciously manage land use scales and elevate land utilization efficiency. "*Landuse*" denotes the ratio of urban industrial land to the total built-up area, which, when managed efficiently, can foster urban compactness (Zhao et al., 2022). However, data from 2020 suggests that excessive expansion of industrial land might result in vacancy issues, negatively impacting city compactness.

4.3.3. Spatial distribution of the driving factors

Furthermore, we spatialize the coefficients of the GTWR to analyze the spatial distribution of the influence strength of each factor (Fig. 7).

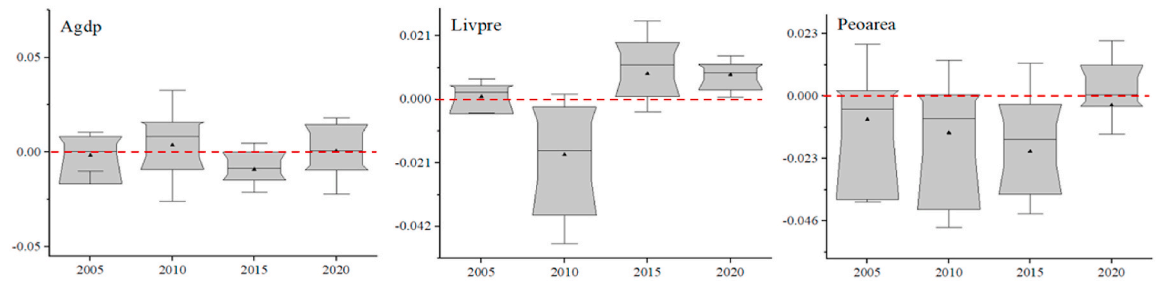
Regarding urban expansion factors and drawing from Fig. 7(a), it is evident that urban expansion factors distinctly promote urban compactness primarily in the economically challenged the western and northeastern region facing significant population outflow. Notably, the adverse effect of *Agdp* on urban compactness is particularly strong in the central and northeastern regions. In contrast to the eastern and southeastern regions, where strict urban planning fosters orderly development, economic growth in the central and northeastern areas tends to produce less compact urban forms. *Livpre* facilitates urban compactness in central and western regions but leads to less compact cities in the coastal and northeastern areas. This trend primarily stems from the coastal and northeastern regions' status as early economic hubs. Due to limited land supply in urban centers, property developers might be driven to focus on urban outskirts, thereby reducing city compactness. *Peoarea* enhances urban compactness solely in northeast China but detracts from it in other regions, with the effect being more discernible in northern China, Tibet, Gansu, Xinjiang, and other areas.

Fig. 7(b) shows that agglomeration efficiency factors positively impact urban compactness, with varying influence across regions. In coastal and northeastern regions, "*Indus*" profoundly affects urban compactness due to their international trade routes, superior transportation and industrial foundations, especially in export and manufacturing sectors (Li et al., 2019). "*Invest*" exerts a milder influence on urban compactness in the northeast and north of China, primarily because these areas have a more uniform economic structure, dominated by heavy industry and energy resources. Consequently, most urban fixed asset investments target these industrial fields. Lastly, "*Roadper*" notably boosts compactness in regions with high mobility and traffic demand, like northeast China and the Pearl River Delta, underscoring its role in promoting compact urban development.

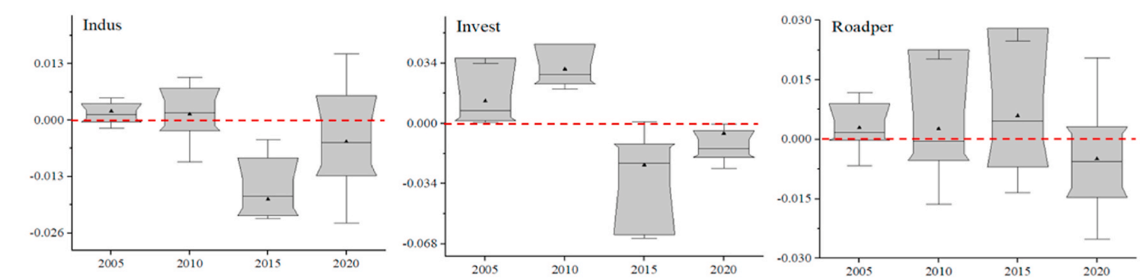
Regarding land and topography factors, our findings align with earlier analyses. Specifically, "*Elevat*" is linked to decentralized urban development in higher-altitude areas like the Qinghai-Tibet Plateau and

Table 4
Descriptive statistical analysis of the strength of action of GTWR model variables.

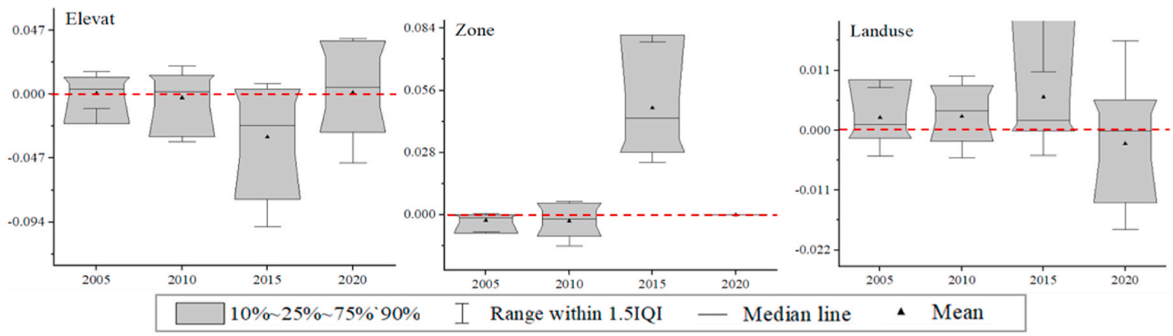
	Urban Expansion			Agglomeration Efficiency			Land and Topography		
Coefficients	*Agdp*	*Livpre*	*Peoarea*	*Indus*	*Invest*	*Roadper*	*Elevat*	*Zone*	*Landuse*
Min	−0.1446	−0.0777	−0.4826	−0.2454	−0.0916	−0.0845	−0.4718	−0.0552	−0.0633
Lower quartile	−0.0073	−0.0054	−0.0172	−0.0125	−0.0168	−0.0035	−0.0183	−0.0017	0.0000
Median	−0.0004	0.0039	−0.0048	0.0009	0.0012	0.0009	−0.0001	0.0000	0.0018
Mean	−0.0015	−0.0002	−0.0114	0.0049	0.0036	0.0017	−0.0080	0.0107	0.0022
Upper quartile	0.0077	0.0097	0.0001	0.0022	0.0241	0.0058	0.0089	0.0239	0.0045
Max	0.0536	0.0971	0.1296	0.0643	0.7093	0.0712	0.1208	0.2023	0.0585
Positive ratio%	47.17%	67.43%	25.57%	55.36%	51.65%	59.66%	49.70%	35.19%	76.46%
Negative ratio%	52.74%	32.49%	74.35%	44.56%	48.27%	40.25%	50.21%	39.75%	23.46%



（a）Coefficients trend of urban expansion factor on urban compactness



（b）Coefficients trend of agglomeration efficiency factors on urban compactness



（c）Coefficients trend of Land and Topography factors on urban compactness

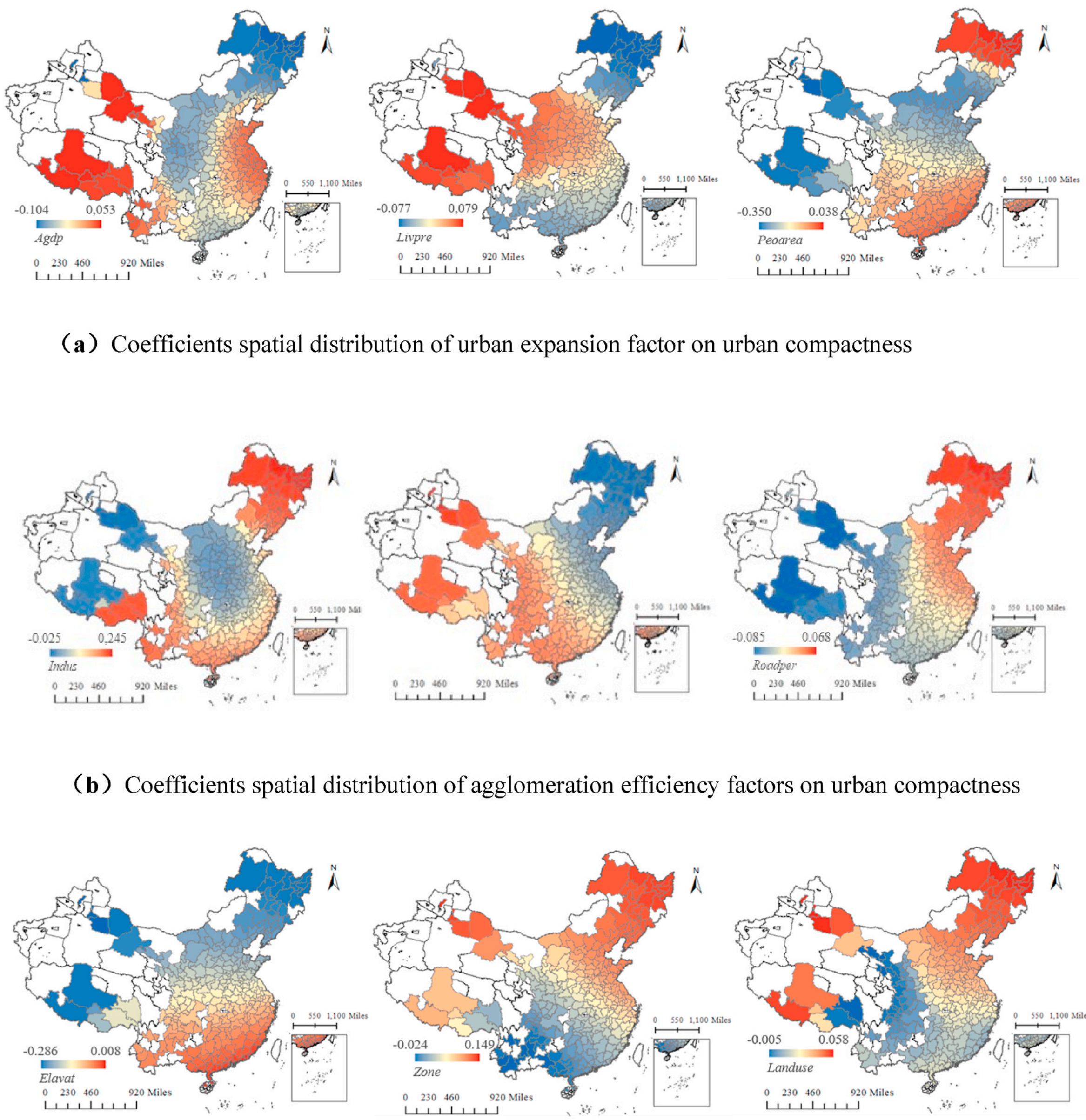
Fig. 6. Coefficients trend of the impact indicators on urban compactness from 2005 to 2020.

the Great and Small Xing'an Mountains in northeast China. In contrast, altitude's correlation with compactness is negligible in other regions. As for *Zone* and *Landuse*, in the northeastern, western, and some northern regions of China, establishing development zones and increasing the industrial land share can significantly enhance urban compactness. Given the abundant developable land in the suburbs of cities in these areas, leveraging the proportion of industrial land use in conjunction with development zones capitalizes on regional benefits. This strategy fosters urban compactness by stimulating the industrial economy and harnessing the clustering effects of essential infrastructure, including roads, water, power, and communication.

5. Discussions

5.1. Significance of this study in compact city theory and practice

Compact city is the sustainable solution to global urban population growth. Our study focuses on evaluating the compactness of urban macro form, addressing the gap in current compact city assessments which tend to emphasize overall evaluations while neglecting morphological compactness (Angel et al., 2020). Specifically, we build upon existing theories to define the multidimensional characteristics of overall compactness (Jia et al., 2022; Kotharkar & Bahadure, 2020; Kotharkar et al., 2014), internal compactness, and external dynamic compactness of urban form, using open-source data to measure these indicators. Considering the comparability between different cities, the spatial heterogeneity of indicators, and the potential preferences of cities at various development stages (Zhang et al., 2019), we employ the



(a) Coefficients spatial distribution of urban expansion factor on urban compactness

(b) Coefficients spatial distribution of agglomeration efficiency factors on urban compactness

(c) Coefficients spatial distribution of Land and Topography factors on urban compactness

Fig. 7. Spatial distribution of the mean value of the impact indicators from 2005 to 2020.

GWPCA method to integrate multidimensional indicators into a comprehensive urban form compactness index. Our theoretical contributions are multifaceted. First, we extend the compact city theory by providing a detailed framework for evaluating morphological compactness, thus addressing a significant gap in current assessments. As shown in our theoretical framework (Fig. 1), we integrate urban morphology theory, spatial structure theory, and evolutionary geography theory to form the basis for our urban form compactness index. Second, we highlight the distinctive features of compact city theory by integrating the dimensions of spatial contour, spatial topology, and spatial dynamics, which are often overlooked. This comprehensive approach provides a robust methodological framework for future research. Third, our findings demonstrate the relevance and applicability of this comprehensive theoretical framework in explaining the formation and dynamics of compact cities. By exploring the constituent elements of the urban form compactness index from both overall and local perspectives, we not only deepen the understanding of the causes of compact city formation but also offer practical insights for urban planning and policymaking.

The application of the urban form compactness index to Chinese prefecture-level cities demonstrates its suitability for compact city practices. On one hand, by integrating the index from multiple dimensions with a spatiotemporal heterogeneity perspective, it provides a clear and comparable view of urban expansion in China over the past two decades. On the other hand, it thoroughly investigates the mechanisms affecting compactness from overall and local perspectives, clarifying key indicators for enhancing urban form compactness at different development stages, which is crucial for the implementation of compact city policies in China. Given the highly spatiotemporal imbalance in the development of Chinese prefecture-level cities, this study includes a sufficiently large sample covering almost all stages of urbanization development (He & Zhou, 2024). Therefore, our research results ensure representativeness and universality on a global scale. Moreover, the use of open-source data effectively ensures that the index can also be applied in developing countries where data might be challenging to obtain.

5.2. The advantages of combining compact urban form index using GWPCA

We integrate multidimensional evaluation metrics of urban form compactness, proposing a framework based on GWPCA method and demonstrates its applicability within Chinese cities. In the context of spatiotemporal evolution, urban forms exhibit homogenous changes while also presenting spatiotemporal differentiation (Deng et al., 2021; Ding et al., 2022; Zhang et al., 2023). Hence, the concept of compactness varies across different types of cities, as reflected in the variation of assessment metric weights. Unlike previous evaluations using a single indicator or multiple indicators with the same weight (Angel et al., 2020; Jia et al., 2022), effectively integrates multidimensional indicators in the context of spatial heterogeneity, facilitating comparability in urban compactness across large-scale urban areas (Liu et al., 2019).

An upward trend was shown in urban compactness quartiles in the eastern and southeastern coastal urban agglomerations, with some eastern regions experiencing a fall back. We concluded that the rapid development of China's cities over the past 20 years has dramatically changed the characteristics of urban form, but differences in the development basis, mode and stage have resulted in spatial heterogeneity. Aligns with the conclusions drawn by Zhao et al. (2020), the degree of compactness of cities on the east coast and in the south has gradually become higher, with a net inflow of population in these areas, and the concentration of population and industries has contributed to the compact development of cities to a certain extent. While for the western regions, urbanization is still in its early stages, and urban expansion has resulted in low compactness (Feng et al., 2024). Additionally, similar to some cities in Latin America, the expansion of western cities is severely constrained by natural terrain (Van der Borght & Pallares Barbera, 2023), preventing the formation of aggregated construction spaces.

5.3. The influence mechanism of urban form compactness index

To further explore how urban form becomes more compact, we use two spatial econometric models to explore the impact mechanism of the index. By concluding previous studies (Dadashpoor & Malekzadeh, 2020; Jia et al., 2022), we summarized urban sprawl, agglomeration efficiency, land use and topography as the main influences on the index. Different from the correlation analysis or global regression models used in previous studies (Schneider & Woodcock, 2008), we realize the spatial correlation of urban form compactness, and use the spatial Durbin model and GTWR to explore the spatiotemporal driving mechanism of urban compactness index globally and locally, which can help us to propose suggestions for compact urban policies in different regions.

The spatial Durbin model elucidates the direct and indirect influences of various factors on urban compactness, highlighting the persistent negative impacts of economic development levels, urban living pressures, and population density. Historical crude and sprawling growth patterns in Chinese cities, preceding new urbanization strategies, facilitated unrestricted urban expansion, diminishing compactness, which is consistent with the findings of Liu et al. (2020). Conversely, factors enhancing agglomeration efficiency, such as investments and infrastructure improvements, positively affect urban compactness by enhancing spatial efficiency and fostering industrial concentration. The positive externalities benefiting neighboring cities are also confirmed in the study by Zhang et al. (2022). Additionally, land and topographic elements like elevation, regional characteristics, and land use exhibit diverse impacts on urban compactness, contingent on a city's geographical setting and developmental history. Moreover, due to differences in policy-driven urban expansion, as shown in the study by Zhu et al. (2024), the effect of development zones on compactness varies.

Utilizing the GTWR model, this study analyzes the trends and distributions of impact indicators on urban compactness from 2005 to 2020. Findings indicate that cities with higher economic development levels typically exhibit lower compactness due to urban sprawl, which is consistent with popular belief (He et al., 2020). While agglomeration efficiency initially supports compactness, its impact can become negative over time. Elevation shows a slight negative correlation with compactness. During China's rapid urbanization (2005–2015), intra-city industrial agglomeration, government investment in fixed assets, and urban road network development enhanced urban compactness. However, under recent urbanization strategies, compact city development increasingly relies on efficient urban-rural integration and the formation of connected city clusters (Liu et al., 2021). Spatially, urban expansion factors particularly promote compactness in China's western and northeastern regions. Agglomeration efficiency varies regionally in its effectiveness in promoting compact city construction, while land use improvements notably enhance compactness in the northeast, west, and parts of northern China through industrial development and infrastructure agglomeration. These findings highlight the spatial and temporal heterogeneity in urban form compactness and its drivers, underscoring the need for tailored urban growth policies (Ou et al., 2019).

5.4. Implications for regional policy

In recent decades, China's urban expanse has seen remarkable growth, with the urban form undergoing significant transformations. This study offers crucial policy suggestions for the Chinese government. Firstly, our urban form compactness index highlights the nuanced urban development patterns in China. The government needs to incorporate the urban form compact index into the urban physical examination indicator system to enhance understanding and supervision of cities (He et al., 2023). Secondly, the government ought to holistically promote urban elements that further compact urban development. This can be achieved by guiding urban growth in terms of direction, mode, and pace through enhancing access to megacities, refining transport infrastructure, and improving the efficiency of industrial agglomeration, all aiming for smart urban growth.

Moreover, in the process of promoting the development of compact urban forms, adopting a city-specific approach and avoiding policy homogenization are crucial. Specifically, urban forms in the southeastern cities are already relatively compact. Local governments need to consider the potential negative effects of compact urban development due to population concentration and industrial development, and balance compact urban forms with environmental risks (Gaigné et al., 2012). On the other hand, the prospect of compact urban forms in central and western cities is not optimistic. Local governments need to strengthen regulation, guide the adjustment of housing structures (Jiuwen et al., 2024), and direct the use of social fixed investments to promote sustainable urban development. Meanwhile, spatial spillover effects merit consideration. It's essential to transcend the limitations imposed by administrative boundaries, harnessing the potential of highly compact cities. By leaning on an improved regional infrastructure and efficient factor flows, a compact and intensive regional development can be actualized.

5.5. Limitations and prospects

However, our research also has some limitations. As for the assessment unit, this study analyzes 296 prefecture-level cities in China, while related studies have shown that there is variability in the evaluation of urban form at the city and county levels, and that many of China's urban growth policies are designed at the prefecture city levels but implemented at the county level (Zhao et al., 2020), thus the study unit can be further refined in the future. In terms of the index evaluation system, we comprehensively evaluated the compactness of cities from the perspectives of form, population, and terrain, but due to the availability of data for Chinese prefecture-level cities, the granularity of the compactness evaluation system can be further refined, such as considering evaluation indicators at the street or building level. Additionally, if more comprehensive and longer-term data becomes available, it will be possible in the future to more intricately understand how different policy tools, such as ecological redlines and land development boundaries, and potential public health events impact urban form.

6. Conclusions

The compactness of urban forms has emerged as a central topic of debate and research in urban studies, and a large number of studies have explored the compact feature of cities. However, few studies have developed multidimensional comprehensive urban form index, especially at the national scale and from the perspective of spatial-temporal database. Taking 296 cities in China as the study area, we establish an urban form compactness index based on three types of typical indicators, and quantify the spatial-temporal heterogeneity of their evolution characteristics and driving mechanisms. The study finds that:

(i)Over the past 20 years, the compactness of Chinese cities has changed significantly. From 2005 to 2020, the compactness of Chinese cities has been improved, and the spatial evolution shows the trend of "high in the southeast and low in the northwest", spreading from the northwest to the southeast. (ii) Overall, urban expansion factors have a negative impact on urban compactness, while agglomeration efficiency factors have a positive impact on agglomeration efficiency. Land and topography factors do not have a significant effect on urban compactness. (iii) Over time, the impact of urban expansion and land indicators are relatively stable, while the agglomeration efficiency indicators have experienced an N-shaped transformation. In terms of spatial heterogeneity, the distribution of urban sprawl factors promotes urban compactness in western and northeastern China, whereas agglomeration efficiency factors have different degrees of influence in different regions, and land use factors effectively improve urban compactness in northeastern, western, and northern regions.

Funding

This research received no external funding.

Declaration of interest statement

All authors disclosed no relevant relationships.

CRediT authorship contribution statement

Xiaoxu Xing: Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Conceptualization. **Weihao Shi:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Xiwei Wu:** Supervision, Software, Methodology, Investigation. **Yang Liu:** Writing – review & editing, Validation, Data curation. **Xiaoxi Wang:** Visualization, Software, Methodology, Investigation. **Yaojun Zhang:** Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2024.103368.

References

Abrantes, P., Rocha, J., Marques da Costa, E., Gomes, E., Morgado, P., & Costa, N. (2017). Modelling urban form: A multidimensional typology of urban occupation for spatial analysis. *Environment and Planning B: Urban Analytics and City Science, 46*(1), 47–65.
Acheampong, R. A., Agyemang, F. S. K., & Abdul-Fatawu, M. (2016). Quantifying the spatio-temporal patterns of settlement growth in a metropolitan region of Ghana. *Geojournal, 82*(4), 823–840.
Ahern, J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology, 28*(6), 1203–1212.
Angel, S., Arango Franco, S., Liu, Y., & Blei, A. M. (2020). The shape compactness of urban footprints. *Progress in Planning, 139*.
Angel, S., Parent, J., & Civco, D. (2010). Ten compactness properties of circles: Measuring shape in geography. *Canadian Geographer/Le Géographe Canadien, 54*, 441–461.
Baruah, N. G., Henderson, J. V., & Peng, C. (2021). Colonial legacies: Shaping african cities. *Journal of Economic Geography, 21*(1), 29–65.
Bibri, S. E. (2020). Compact urbanism and the synergic potential of its integration with data-driven smart urbanism : An extensive interdisciplinary literature review. *Land Use Policy, 97*.
Bourne, L. S. (1982). *Internal structure of the city : Readings on urban form, growth, and policy*.
Burton, E. (2002). Measuring urban compactness in UK towns and cities. *Environment and Planning B: Planning and Design, 29*(2), 219–250.
Chakraborty, S., Novotný, J., Maity, I., Lemoine-Rodríguez, R., & Follmann, A. (2024). Same planet but different worlds! Diverging convergence pattern of urban form typologies across 413 cities with million+ inhabitants and their sustainability trade-offs. *Habitat International, 145*, Article 103024.
Chen, H., Jia, B., & Lau, S. S. Y. (2008). Sustainable urban form for Chinese compact cities: Challenges of a rapid urbanized economy. *Habitat International, 32*(1), 28–40.
Chen, M., Liu, W., & Lu, D. (2016). Challenges and the way forward in China's new-type urbanization. *Land Use Policy, 55*, 334–339.
Co-operation, O. f. E., Development. (2012). *Compact city policies: A comparative assessment, oecd*.
Cohen, B. (2004). Urban growth in developing countries: A review of current trends and a caution regarding existing forecasts. *World Development, 32*(1), 23–51.
Dadashpoor, H., & Malekzadeh, N. (2020). Driving factors of formation, development, and change of spatial structure in metropolitan areas: A systematic review. *Journal of Urban Management, 9*(3), 286–297.
Dantzig, G. B., & Saaty, T. L. (1973). *Compact city: A plan for a liveable urban environment*.
Deng, H., Zhang, K., Wang, F., & Dang, A. (2021). Compact or disperse? Evolution patterns and coupling of urban land expansion and population distribution evolution of major cities in China, 1998–2018. *Habitat International, 108*, Article 102324.
Dhanani, A., Tarkhanyan, L., & Vaughan, L. (2017). Estimating pedestrian demand for active transport evaluation and planning. *Transportation Research Part A: Policy and Practice, 103*, 54–69.
Ding, G., Guo, J., Pueppke, S. G., Ou, M., Ou, W., & Tao, Y. (2022). Has urban form become homogenizing? Evidence from cities in China. *Ecological Indicators, 144*, Article 109494.
Feng, X., Wang, S., Li, Y., Yang, J., Lei, K., & Yuan, W. (2024). Spatial heterogeneity and driving mechanisms of carbon emissions in urban expansion areas: A research framework coupled with patterns and functions. *Land Use Policy, 143*, Article 107209.
Gaigné, C., Riou, S., & Thisse, J.-F. (2012). Are compact cities environmentally friendly? *Journal of Urban Economics, 72*(2), 123–136.
Gao, B., Huang, Q., He, C., & Ma, Q. (2015). Dynamics of urbanization levels in China from 1992 to 2012: Perspective from DMSP/OLS nighttime light data. *Remote Sensing, 7*, 1721–1735. https://doi.org/10.3390/rs70201721
Garcia Manzato, G., & Rodrigues da Silva, A. N. (2009). Spatial-temporal combination of variables for monitoring changes in metropolitan areas. *Applied Spatial Analysis and Policy, 3*(1), 25–44.
Gong, P., Liang, S., Carlton, E. J., Jiang, Q., Wu, J., Wang, L., & Remais, J. V. (2012). Urbanisation and health in China. *The Lancet, 379*(9818), 843–852.
Han, J., Kang, X., Yang, Y., & Zhang, Y. (2022). Geographically and temporally weighted principal component analysis: A new approach for exploring air pollution non-stationarity in China, 2015-2019. *Journal of Spatial Science, 68*(3), 451–468.
He, H. M., Ren, Y. T., Shen, L. Y., Xiao, J., Lai, Y. Y., Yang, Y., & Zhang, L. Y. (2023). A guiding methodology for "urban physical examination": Indicator checklist, benchmark setting and empirical study. *Sustainable Cities and Society, 98*, Article 104835.
He, S., & Wu, F. (2007). Socio-spatial impacts of property-led redevelopment on China's urban neighbourhoods. *Cities, 24*, 194–208.
He, S., Yu, S., Li, G., & Zhang, J. (2020). Exploring the influence of urban form on land-use efficiency from a spatiotemporal heterogeneity perspective: Evidence from 336 Chinese cities. *Land Use Policy, 95*.
He, D., Zhang, Z., & Zhang, W. (2009). How large will be the effect of China's fiscal stimulus package on output and employment? *Pacific Economic Review, 14*(5), 730–744.
He, X., & Zhou, Y. (2024). Urban spatial growth and driving mechanisms under different urban morphologies: An empirical analysis of 287 Chinese cities. *Landscape and Urban Planning, 248*, Article 105096.
Hou, Y. M., Li, Y. Y., Li, J., Huang, Q. X., Duan, X. Y., Feng, X. Y., & Zhu, G. L. (2023). Simulating the dynamics of urban land quantity in China from 2020 to 2070 under the Shared Socioeconomic Pathways. *Applied Geography, 159*.

Huang, B., Wu, B., & Barry, M. (2010). Geographically and temporally weighted regression for modeling spatio-temporal variation in house prices. *International Journal of Geographical Information Science, 24*(3), 383–401.
Jabareen, Y. R. (2006). Sustainable urban forms:Their typologies, models, and concepts. *Journal of Planning Education and Research, 26*(1), 38–52.
Jia, M., Zhang, H., & Yang, Z. (2022). Compactness or sprawl: Multi-dimensional approach to understanding the urban growth patterns in Beijing-Tianjin-Hebei region, China. *Ecological Indicators, 138*, Article 108816.
Jiuwen, S., Xiaoxu, X., Qiangmin, X., & Weihao, S. (2024). Impact of urban form on housing affordability stress in Chinese cities: Does public service efficiency matter? *Cities, 145*, Article 104682.
Kaza, N. (2022). Landscape shape adjusted compactness index for urban areas. *Geojournal, 87*(2), 1399–1409.
Kelobonye, K., Xia, J. C., Swapan, M. S. H., McCarney, G., & Zhou, H. (2019). Drivers of change in urban growth patterns: A transport perspective from perth, western Australia. *Urban Science, 3*(2).
Kirby, M. G., Scott, A. J., Luger, J., & Walsh, C. L. (2023). Beyond growth management: A review of the wider functions and effects of urban growth management policies. *Landscape and Urban Planning, 230*, Article 104635.
Kotharkar, R., & Bahadure, P. (2020). Achieving compact city form through density distribution: Case of Indian Cities. *Journal of Urban Planning and Development, 146*(1), Article 04019022.
Kotharkar, R., Bahadure, P., & Sarda, N. (2014). Measuring compact urban form: A case of nagpur city, India. *Sustainability, 6*(7), 4246–4272.
Kropf, K. (2009). Aspects of urban form. *Urban Morphology, 13*, 105–120.
Lan, T., Shao, G., Xu, Z., Tang, L., & Sun, L. (2021). Measuring urban compactness based on functional characterization and human activity intensity by integrating multiple geospatial data sources. *Ecological Indicators, 121*, Article 107177.
LeSage, J., & Pace, R. K. (2009). *Introduction to spatial econometrics*. Chapman and Hall/CRC.
Li, Y. C., & Ben, D. (2022). Dynamics in the polycentric development of Chinese cities, 2001-2016. *Urban Geography, 43*(2), 272–292.
Li, K., Gao, S., Liao, Y., Luo, K., & Wang, S. (2022). The impact of development zones on China's urbanization from the perspectives of the population, land, and the economy. *Land, 11*(10).
Li, Z., Wang, F., Kang, T., Wang, C., Chen, X., Miao, Z., Zhang, L., Ye, Y., & Zhang, H. (2022). Exploring differentiated impacts of socioeconomic factors and urban forms on city-level CO_2 emissions in China: Spatial heterogeneity and varying importance levels. *Sustainable Cities and Society, 84*, Article 104028.
Li, W., Wang, D., Li, H., Wang, J., Zhu, Y., & Yang, Y. (2019). Quantifying the spatial arrangement of underutilized land in a rapidly urbanized rust belt city: The case of Changchun City. *Land Use Policy, 83*, 113–123.
Liu, Y., Chen, X., & Liu, D. (2020). How does urban spatial structure affect economic growth? Evidence from landsat data in China. *Journal of Economic Issues, 54*(3), 798–812.
Liu, H., Huang, B., Zhan, Q., Gao, S., Li, R., & Fan, Z. (2021). The influence of urban form on surface urban heat island and its planning implications: Evidence from 1288 urban clusters in China. *Sustainable Cities and Society, 71*, Article 102987.
Liu, X., Qin, M., & Li, S. (2019). Urban spatial structure and labour income. *The Journal of World Economy, 42*(4), 123–148.
Liu, L., & Tian, Y. (2022). Does the compact city paradigm help reduce poverty? Evidence from China. *International Journal of Environmental Research and Public Health, 19*(10).
Liu, X., & Wang, M. (2016). How polycentric is urban China and why? A case study of 318 cities. *Landscape and Urban Planning, 151*, 10–20.
Lu, H., Zhang, M., Sun, W., & Li, W. (2018). Expansion analysis of yangtze River Delta urban agglomeration using DMSP/OLS nighttime light imagery for 1993 to 2012. *ISPRS International Journal of Geo-Information, 7*. https://doi.org/10.3390/ijgi7020052
Luo, J., Zhang, X., Wu, Y., Shen, J., Shen, L., & Xing, X. (2018). Urban land expansion and the floating population in China: For production or for living? *Cities, 74*, 219–228.
Mariaflavia, H. (2020). Cities in bad shape: Urban geometry in India. *The American Economic Review, 110*(8), 2377–2421.
Miguel, G.-A., Miriam, H.-R., & Linna, L. (2016). The causes of urban sprawl in Spanish urban areas: A spatial approach. *Spatial Economic Analysis, 11*(2), 219–247.
Mishra, S. V. (2018). Urban deprivation in a global south city-a neighborhood scale study of Kolkata, India. *Habitat International, 80*, 1–10.
Newman, P. (1987). *Gasoline consumption and cities: A comparison of U.S. Cities with a global survey and some implications*. Murdoch University.
Ou, J., Liu, X., Wang, S., Xie, R., & Li, X. (2019). Investigating the differentiated impacts of socioeconomic factors and urban forms on CO_2 emissions: Empirical evidence from Chinese cities of different developmental levels. *Journal of Cleaner Production, 226*, 601–614.
Peng, C., Song, M., & Han, F. (2017). Urban economic structure, technological externalities, and intensive land use in China. *Journal of Cleaner Production, 152*, 47–62.
Reis, J. P., Silva, E. A., & Pinho, P. (2016). Spatial metrics to study urban patterns in growing and shrinking cities. *Urban Geography, 37*(2), 246–271.
Robinson, C., Lindley, S., & Bouzarovski, S. (2019). The spatially varying components of vulnerability to energy poverty. *Annals of the Association of American Geographers, 109*(4), 1188–1207.
Scheuer, S., Haase, D., & Volk, M. (2016). On the nexus of the spatial dynamics of global urbanization and the age of the city. *PLoS One, 11*, Article e0160471.
Schneider, A., & Woodcock, C. E. (2008). Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information. *Urban Studies, 45*(3), 659–692.
Schwarz, N. (2010). Urban form revisited—selecting indicators for characterising European cities. *Landscape and Urban Planning, 96*(1), 29–47.
Shi, K., Liu, G., Cui, Y., & Wu, Y. (2023). What urban spatial structure is more conducive to reducing carbon emissions? A conditional effect of population size. *Applied Geography, 151*, Article 102855.
Shukla, A., Jain, K., Ramsankaran, R. A. A. J., & Rajasekaran, E. (2021). Understanding the macro-micro dynamics of urban densification: A case study of different sized Indian cities. *Land Use Policy, 107*.
Thinh, N. X., Arlt, G., Heber, B., Hennersdorf, J., & Lehmann, I. (2002). Evaluation of urban land-use structures with a view to sustainable development. *Environmental Impact Assessment Review, 22*(5), 475–492.
Van der Borght, R., & Pallares Barbera, M. (2023). How urban spatial expansion influences CO_2 emissions in Latin american countries. *Cities, 139*, Article 104389.
Wang, Q., Liu, X., & Li, Y. (2021). Spatial structure, city size and innovation performance of Chinese cities. *China Industrial Economics*, (5), 114–132 (In Chinese).
Wang, J., Qu, S., Peng, K., & Feng, Y. (2019). Quantifying urban sprawl and its driving forces in China. *Discrete Dynamics in Nature and Society, 2019*.
Wang, S., Wang, J., Fang, C., & Li, S. (2019). Estimating the impacts of urban form on CO_2 emission efficiency in the Pearl River Delta, China. *Cities, 85*, 117–129.
Wu, Y., Luo, J., Zhang, X., & Skitmore, M. (2016). Urban growth dilemmas and solutions in China: Looking forward to 2030. *Habitat International, 56*, 42–51.
Wu, R., Zhang, Y., Dai, M., Li, Q., & Sun, C. (2023). The heterogeneity of the drivers of urban form in China: Perspectives from regional disparities and development stage variations. *Land, 12*(7), 1436.
Xia, C., Yeh, A. G.-O., & Zhang, A. (2020). Analyzing spatial relationships between urban land use intensity and urban vitality at street block level: A case study of five Chinese megacities. *Landscape and Urban Planning, 193*, Article 103669.
Xia, C., Zhang, A. Q., & Yeh, A. G. O. (2022). The varying relationships between multidimensional urban form and urban vitality in Chinese megacities: Insights from a comparative analysis. *Annals of the Association of American Geographers, 112*(1), 141–166.
Xiaoxu, X., Qiangmin, X., & Weihao, S. (2024). Impact of urban compactness on carbon emission in Chinese cities: From moderating effects of industrial diversity and job-housing imbalances. *Land Use Policy, 143*, Article 107213.
Yi, K. P., Zeng, Y., & Wu, B. F. (2016). Mapping and evaluation the process, pattern and potential of urban growth in China. *Applied Geography, 71*, 44–55.
Yoon, C.-J. (2020). Between the ideal and reality of city resizing policy: Focused on 25 cases of compact city plans in Japan. *Sustainability, 12*(3).
Yuan, M., Huang, Y. P., Shen, H. F., & Li, T. W. (2018). Effects of urban form on haze pollution in China: Spatial regression analysis based on PM2.5 remote sensing data. *Applied Geography, 98*, 215–223.
Zhang, P., Pan, J., Xie, L., Zhou, T., Bai, H., & Zhu, Y. (2019). Spatial–temporal evolution and regional differentiation features of urbanization in China from 2003 to 2013. *ISPRS International Journal of Geo-Information, 8*(1).
Zhang, W., Wang, B., Wang, J., Wu, Q., & Wei, Y. D. (2022). How does industrial agglomeration affect urban land use efficiency? A spatial analysis of Chinese cities. *Land Use Policy, 119*.
Zhang, X., Zhang, Q. Y., Zhang, X. Y., & Gu, R. X. (2023). Spatial-temporal evolution pattern of multidimensional urban shrinkage in China and its impact on urban form. *Applied Geography, 159*.
Zhao, A., Huang, J., Gao, F., Meng, H., & Peng, C. (2022). Regional allocation of industrial land in industrializing China: Does spatial mismatch exist? *Landscape Research, 48*(3), 396–411.
Zhao, F., Tang, L., Qiu, Q., & Wu, G. (2020). The compactness of spatial structure in Chinese cities: Measurement, clustering patterns and influencing factors. *Ecosystem Health and Sustainability, 6*(1), Article 1743763.
Zhou, G., & He, Y. (2007). The influencing factors of urban land expansion in Changsha. *Journal of Geographical Sciences, 17*(4), 487–499.
Zhou, W., Jiao, M., Yu, W., & Wang, J. (2019). Urban sprawl in a megaregion: A multiple spatial and temporal perspective. *Ecological Indicators, 96*, 54–66.
Zhou, Y., Tong, C., & Wang, Y. (2022). Road construction, economic growth, and poverty alleviation in China. *Growth and Change, 53*(3), 1306–1332.
Zhu, J., Tu, Y., & Zhu, J. (2024). Institution-driven urban sprawl in China: Evidence from wuhan. *Cities, 148*, Article 104899.