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Multidimensional disparities in urban liveability across Chinese non-core cities: a typological exploration based on carbon emissions differences

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Decarbonisation has increasingly become a major policy direction globally, deeply intertwined with urban socio-economic development. However, the connection between such a process and urban liveability remains underexplored. This oversight is particularly consequential for non-core cities, due to limited resources, institutional constraints, and weaker economic structures in these smaller cities. Thus, decarbonisation often places extra restrictions on their socio-economic progress, further affecting their liveability. Focusing on Chinese ordinary prefecture-level cities, this study sheds light on the structure of carbon emissions in Chinese non-core cities and their liveability performance. The typology exploration is employed to understand to what extent these non-core cities demonstrate different carbon emission characteristics and whether there are significant disparities in urban liveability among the different types. On this basis, the relationships between carbon emissions and liveability across different city types are further explored by applying correlation analysis and coupling analysis. The findings reveal a strong positive correlation between the two, indicating a prevalent reliance on carbon-intensive socio-economic activities for urban liveability. While economic strength, developmental space, and employment potential contribute most significantly to liveability, they are also tightly coupled with emissions. More importantly, four distinctive city types are defined, each revealing notable heterogeneity in liveability performance and exhibiting distinct patterns in their relationship with carbon emissions. This study contributes by highlighting the risks of decarbonisation trajectories on non-core cities and calls for targeted, context-sensitive strategies that balance emission reduction with liveability preservation.

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Introduction

Concerns over carbon emissions are being taken increasingly seriously by policymakers globally (Belaïd & Unger, 2024; Kenny et al., 2010). As the world's largest energy consumer, China faces mounting pressure to address such crises, prompting the government to introduce a series of decarbonisation policies (Du et al., 2021; Zhang et al., 2020). Over the past two decades, the majority of Chinese cities have adopted carbon reduction strategies in response to central government initiatives: in the 2020 s, China pledged to reduce its carbon intensity by 60–65%, reach peak carbon emissions by 2030, and achieve carbon neutrality by 2060 (Wang et al., 2019). This commitment has since become a key guideline for the future development of Chinese cities (Liu & Qin, 2016).

In this context, decarbonisation strategies and their effectiveness have been widely studied, with a growing body of research examining the relationship between carbon emissions and specific urban socio-economic conditions (Chuai et al., 2024; Hunter et al., 2023). Understanding these relationships can help policymakers develop more targeted and context-sensitive interventions to achieve low-carbon goals while accommodating ongoing urban growth (Li, 2022). Such insights also provide valuable references for cities with similar development profiles to collaborate on low-carbon initiatives, rather than uniformly pursuing potentially unrealistic objectives (Scanu, 2015), as untargeted policies can instead exacerbate the carbon emissions deterioration because of the socio-economic disparities (Wang & Liu, 2024).

Therefore, it is essential to consider the socio-economic variability across cities when addressing such issues. Previous research has produced a substantial body of work to understand such variability. For instance, scholars have examined the implications of carbon emissions for urban growth and developed evaluation frameworks to assess differences in city-level performance and to identify various barriers to decarbonisation (Mahmood et al., 2024). Additionally, decarbonisation outcomes have been shown to vary significantly across cities. For example, related policies tend to be more effective in large, non-resource-based cities than in smaller cities dominated by traditional heavy industries (Qiu et al., 2021). However, when considering the differences in decarbonisation across cities, existing research tends to emphasise macro-level variables such as industrial transformation (Ribeiro et al., 2019), while often overlooking a crucial dimension: urban liveability. Specifically, the question of whether carbon emission patterns are linked to the multi-dimensional aspects of liveability and well-being across different cities remains unanswered.

The benefits of decarbonisation should not only promote the quality of economic growth but also enhance the livelihoods of local residents. Liveability refers to the overall quality of life experienced by residents in a given urban area (Kashef, 2016). It encompasses a range of dimensions, including economic potential, social vitality, housing affordability, access to public services, environmental quality, and employment opportunities (Benita et al., 2021). In a word, a highly liveable city enables its residents to comfortably meet their daily needs, participate fully in social and economic life, and maintain both physical and mental well-being. Ideally, decarbonisation should reinforce liveability, given its potential to improve economic structure, restore environmental and ecological systems, and foster greater social inclusion (Horne et al., 2024). However, overly aggressive decarbonisation efforts have also brought significant challenges to cities. For instance, scholars have documented how the energy transition in Europe has disproportionately impacted low-income households, leading to rising energy poverty (Janikowska et al., 2024). Similarly, environmental regulations aimed at decarbonisation have, to some extent, promoted the optimisation of urban economic structures, but they have also brought obstacles to local growth and increased pressure on industrial transformation, even workforce displacement (Qin et al., 2022).

Faced with such a problem, big cities are often more adaptable to those decarbonisation interventions, because of their advanced economic structure, which tends to have more knowledge-intensive and high-profitability sectors (Wu et al., 2025). Meanwhile, those big cities have sufficient resources and capabilities to cope with these interventions, including the power in policymaking, the strong socio-economic foundation, and the implementation of innovative technologies (Linton et al., 2022). Non-core cities, on the other hand, cannot adapt well to the decarbonisation wave due to their lack of inherent endowments, low political voice, and traditional economic structures (Qiu et al., 2021).

These smaller non-core cities far outnumber the big regional cores and accommodate a substantial share of the national population in China; the value of liveability in such cities is even more pronounced, yet it has received insufficient attention from both scholars and policymakers.

Therefore, non-core cities are being focused on in this study. Ordinary prefecture-level cities are the focus of this study, excluding those with higher administrative levels such as centrally administered municipalities, sub-provincial cities, and provincial capitals (Wei, 2015). Government authorities have also begun to pay increasing attention to these cities in an effort to build a more balanced and coordinated regional system. For instance, the 14th Five-Year Plan highlights the multidimensional potential of non-core cities in terms of functional diversity, social vitality, and cultural revitalisation (Du et al., 2024a). This underscores the growing recognition of the need to focus on non-core cities.

To conclude, in the decarbonisation trajectory, non-core cities often face greater vulnerabilities regarding liveability, as they are more likely to suffer from limited resources, weaker governance capacity, and institutional constraints. Also, effective decarbonisation strategies require a nuanced understanding of the variability in both carbon emissions and liveability across different cities, a dimension that remains underexplored in existing literature. Therefore, this study focuses on Chinese non-core cities to examine whether distinct patterns of carbon emissions are accompanied by differentiated liveability performance. Accordingly, this paper is structured around three key objectives:

- To identify the compositional variability of carbon emissions among non-core cities in China;
- To examine the heterogeneity of urban liveability in relation to the emission differences;
- To investigate the relationships between carbon emissions and liveability across different non-core cities.

The results are expected to provide valuable insights for designing more targeted decarbonisation trajectories that aim to reduce carbon emissions while safeguarding urban liveability in non-core cities, particularly in light of the variability in carbon emission structures and the associated heterogeneity in liveability across cities. To this end, the methodological approach is innovatively grounded in a typological perspective. We first identify distinct types of non-core cities based on differences in the composition of their carbon emissions. Building upon this typology, we then examine the heterogeneity of liveability performance, the correlation between carbon emissions and liveability, and the underlying mechanisms.

On this basis, 237 non-core cities are selected. The next section introduces the relevant conceptual understanding and the specific research design. Section 3 reports the research results, in which the study finds that Chinese non-core cities can be classified into four

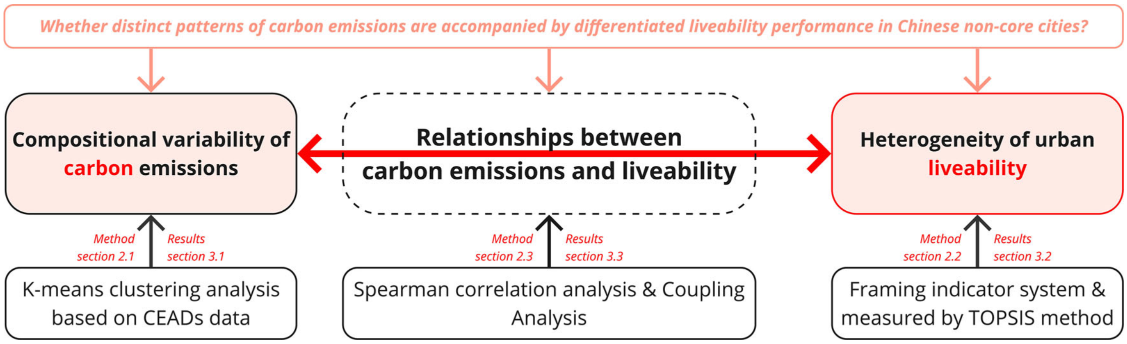

Fig. 1 Research framework.

types based on their carbon emission characteristics. Based on the distinction between various types, the relationship between them and carbon emissions is also explored. Section 4 provides an in-depth discussion of the findings and further contributes policy recommendations on the decarbonisation pathway for non-core cities. This paper ends in Section 5 as a conclusion. To further support the main body of this study, the supplementary material is provided, investigating the correlations among various liveability dimensions and examining the underlying mechanisms between carbon emissions and liveability, using variables that reflect representative decarbonisation pathways in the Chinese context.

Conceptual understanding and research design

A review of the current literature identifies key gaps, which in turn inform a more concrete and feasible research design pathway. First, a growing body of research has examined the relationship between carbon emissions and urban development, highlighting the roles of urban expansion, industrial structure, and energy consumption (Zhang et al., 2020; Lombardi et al., 2017). These studies provide a solid foundation for understanding the drivers of carbon emissions and constructing measurement frameworks (Deutch, 2017; Engo, 2021). However, there is limited attention to the compositional structure of carbon emissions. Most studies treat the city as a single emission entity, focusing on total volume or intensity, while overlooking how variations in emission sources reflect deeper urban characteristics and development patterns.

Meanwhile, liveability has gained increasing academic and policy attention as a key indicator of urban development quality. Although scholars have begun to adopt a more multidimensional framework (Okulicz-Kozaryn & Valente, 2019; Garrone et al., 2018; Pacione, 1990), facing decarbonisation, liveability is still often narrowly interpreted as environmental or ecological meanings (e.g., Fakher, 2019). This is particularly problematic for non-core cities, where economic development and related factors remain essential to support basic livelihood and productivity needs (Ruszczyk et al., 2023). Moreover, while previous studies have acknowledged inter-city heterogeneity, they often rely on administrative divisions (e.g., east-central-west, or provincial-level analysis) or broad economic classifications (e.g., Zhang et al., 2022). Few studies adopt a typological perspective that classifies cities based on the composition of their carbon emissions, an approach that enables a more nuanced understanding of the characteristics and emission patterns unique to different types of cities. The use of a typological approach thus offers a new lens for understanding inter-city heterogeneity and better connects the two core concepts of carbon emissions and liveability. On this basis, a more detailed research design is developed based on conceptual understanding to address three research objectives (Fig. 1).

Identifying compositional variability by typological exploration. There are well-validated definitions and data sources for the components of carbon emissions for Chinese cities. The research group Carbon Emission Accounts and Datasets for Emerging Economies (CEADs) measures the carbon emissions of Chinese prefecture-level cities based on six components, namely, Agriculture, Service, Industrial, Household, Transportation, and Energy. These six components are also recognised as the main sources of urban carbon emissions, covering various activities (Lombardi et al., 2017). Likewise, the components also have the potential to express the different carbon emissions characteristics of cities, since they are often strongly related to the socio-economic status of a city. For example, carbon components can characterise the economic structure and further diagnose the challenges in achieving decarbonisation (Yang et al., 2020).

Based on this, we aim to classify cities according to the compositional differences in their carbon emissions, then identify their underlying variability. K-means clustering analysis is considered an effective approach, as it operates by calculating the Euclidean distance between observations across specific metrics and grouping those with similar characteristics into the same cluster (Wagih et al., 2020). This method has been widely validated as a reliable and accurate tool for urban typology (e.g., Cardoso et al., 2025). It effectively integrates multidimensional characteristics through holistic measurements and generates centroids, typically the mean value across all dimensions, that represent the defining traits of each group, thereby enhancing the model's explainability (Bobkova et al., 2021).

In this way, K-means balances objectivity and simplicity more effectively than many other clustering techniques. For instance, hierarchical clustering, which constructs nested tree structures, is often used in network exploration, such as identifying user communities on social media or revealing hierarchical social relationships (Sinha et al., 2020). However, it is generally more suited to small-scale networks and requires subjective judgement to determine the final number of clusters (Hasan et al., 2021). DBSCAN, on the other hand, is frequently applied in intra-urban scale spatial analyses (Tu et al., 2022). It excels at identifying density-based clusters in irregular spatial patterns, such as hotspots or outliers (Deng, 2020). While DBSCAN is effective in detecting dense or irregular clusters, it is sensitive to parameter selection and may produce unstable results when applied to high-dimensional urban data.

Given the focus on identifying city types based on carbon emission composition, rather than exploring hierarchical relationships or detecting spatial density, K-means emerges as the most appropriate method for the sample of 237 non-core Chinese cities. Its emphasis on optimising inter-group and intra-group differences aligns well with the goals of classification. Therefore, we use K-means clustering analysis in R programming based on the CEADs carbon emissions data to generate a typology of non-core cities. The proportion of total emissions of the six components is calculated, and they are used as the basic attributes of each city for the clustering analysis.

Examining the heterogeneity based on measuring urban liveability

Conceptual understanding of urban liveability and indicators selection. The discussion of urban liveability in China originates from the critique of the development model that pursues fast economic growth in an unsustainable way (Liang et al., 2020). To facilitate the transition, liveability is emphasised as a fundamental goal based on the vision of improving the well-being of citizens: the implementation plan for the 14th Five-Year Plan for New Urbanisation in 2022 interprets liveability as the enhancement of urban public services and community livelihood support regarding education, healthcare, and pensions; the convenience and efficiency of infrastructures; the living environment quality, and stable market for the housing; and urban regeneration and spatial improvement (CNDRC, 2022). In addition to these perspectives related to daily life, liveability in such an authoritative document is expanded as a comprehensive framework to include the dimensions of vitality, innovation, greenness, and cultural humanity.

Such a "comprehensive" liveability framework is particularly relevant for non-core cities. On one hand, compared to core cities with highly concentrated functions, non-core cities are more directly responsible for supporting everyday life, making access to basic services such as education, healthcare, and housing. On the other hand, non-core cities still face various constraints in their development. Policies would be ineffective if they overlook the distinct needs and developmental stages of these cities. Therefore, localising comprehensive liveability assessment frameworks to the specificity of non-core cities has become a critical yet underexplored task.

Unlike core cities that have largely completed functional concentration, most non-core cities remain in developing phases (Parkinson et al., 2016). Therefore, their liveability also accounts for future development potential, such as economic growth and population concentration. Second, social life and everyday experience are also more central to non-core cities. While core cities emphasise global connectivity, advanced services, or headquarters economy (Pan et al., 2015), non-core cities function primarily as places of local residence and community (Bell & Jayne, 2009). Residents value affordable housing, neighbourhood cohesion, and cultural belonging, factors that shape local identity and everyday satisfaction. Moreover, non-core cities rely less on high-end research clusters and more on fostering support for small businesses and entrepreneurship (Mayer & Motoyama, 2020). In this way, innovation remains a key element of liveability, and non-core cities may possess unique advantages in this regard, such as greater flexibility, lower operating costs, and stronger local networks (Knox & Mayer, 2013). Finally, the liveability of non-core cities largely depends on meeting the fundamental needs of daily life, such as basic public services and environmental quality. Unlike core cities that often benefit from concentrated resources and advanced service systems, non-core cities must build liveability by ensuring the availability, accessibility, and quality of essential services and a healthy living environment (Thondoo et al., 2020). On this basis, seven dimensions and specific indicators are framed for measuring the liveability in non-core cities:

- Urban size does not necessarily equate to higher liveability; core cities often face challenges of overcrowding. However, for non-core cities, larger urban size tends to reflect socio-economic agglomeration benefits and advanced functions and services (McCrea & Walters, 2012; Pacione, 1990). Moreover, these non-core cities are increasingly recognised as vital carriers for promoting balanced regional development (CNDRC, 2021). This study adopts population and GDP as classical indicators of socio-economic agglomeration. In addition, built-up area is included to capture a city's development capacity. This is particularly relevant for non-core cities, where land availability and construction potential often determine the feasibility of future growth and improvements in urban functions (Martino et al., 2021).
- Housing and living environments are critical bottlenecks influencing urban liveability (Mouratidis, 2020). This study adopts two key indicators, housing supply and affordability. For non-core cities, this is not only a matter of improving living standards but also an important strategy to enhance urban attractiveness, especially in the context of shrinking or ageing demographics (Fernandez & Hartt, 2022). In addition, the quality of the housing environment is considered essential for residents' well-being in non-core cities, where natural amenities often play a key role in supporting physical and mental health and building a sense of place (Zhao et al., 2021).
- Social vitality is a crucial component of liveability and plays a significant role in attracting population and talent by contributing to a high quality of life (Lan et al., 2020; Ruszczyk et al., 2023), which brings great value to non-core cities, as they often struggle with population loss, ageing demographics, and weaker cultural activities (Knox & Mayer, 2013). The study considers three key indicators. First, daily life vitality is assessed using the nighttime light index, which serves as a spatial proxy for the intensity of socio-economic activity, aiming at revitalising public life and extending activity spaces for non-core cities (Zhang et al., 2022). Second, cultural vitality is measured by the number of library book collections, reflecting access to cultural resources and opportunities for civic engagement (Loach et al., 2017). In non-core cities, such facilities play a crucial role in maintaining cultural participation and local cohesion. Third, information vitality is introduced to reflect the digital visibility. The Baidu Index, indicating the frequency with which a city is searched online, represents a city's online attractiveness (Du et al., 2024b). For non-core cities, enhancing digital presence can amplify their identity and attract more visitors and investment for greater vitality.
- Urban innovation capacity plays a vital role in enhancing education quality, driving industrial transformation, and improving living standards (Kim et al., 2021). First, the number of patents is selected to proxy practical innovation (Liu et al., 2020). Second, education for innovation, reflected by enrolment or investment in higher education, represents the foundation of a creative environment and intergenerational capacity-building (Peng & Xu, 2024). Third, government expenditure on science and technology is included to indicate institutional support for innovation (Xiong et al., 2020), which is especially important in non-core cities where private investment may be limited.
- Urban employment conditions shape not only the income levels but also the sense of self-worth and social integration of residents, making it a critical dimension of urban liveability (Wang & Shao, 2022). Facing constraints in attracting external capital and high-end industries, non-core cities rely more on inclusive job creation and grassroots entrepreneurship to sustain their local economies. Income is considered the primary indicator to reflect

the overall employment level. Also, this study evaluates employment potential through the number of large enterprises, as they serve not only as major job providers but also play a key role in developing local human capital and facilitating knowledge diffusion, especially in smaller cities (Yan, 2021). Moreover, the entrepreneurial environment is assessed using the Financial Inclusion Index, which reflects the digital infrastructure, access to financial services, and institutional support available to small businesses (Kashef, 2016).

- Urban greenness plays a crucial role in shaping liveability. This study incorporates three indicators: PM 2.5 to reflect environmental quality, the NDVI index to represent ecological quality, and carbon intensity as a proxy for energy efficiency. For non-core cities, good environmental quality and higher ecological coverage contribute to a greener urban-scape, offering accessible natural spaces that support everyday well-being, becoming signature features of liveable small cities (Liu et al., 2019). Meanwhile, improving energy efficiency is also crucial for non-core cities undergoing industrial transition, as it reflects their efforts to decouple socio-economic activities from environmental costs (Ji et al., 2020).
- Urban public facilities and social support, conceptualised here as a public good, provide essential support for daily life (Frick & Rodríguez-Pose, 2018). This dimension includes three indicators: the coverage of pension insurance for employees, which reflects the city's capacity to ensure social protection and long-term security as social welfare guarantee; the number of primary school teachers per capita, representing the adequacy and accessibility of basic education provision as basic education support; and the total length of urban roads, which captures the quality of urban infrastructure that underpins residents' mobility and service access (Zhan et al., 2018).

Although this study proposes a multidimensional indicator system covering economic, social, and environmental aspects to evaluate the liveability of non-core cities, several potential limitations remain. First, the general applicability of the indicators may not fully capture local specificities. Despite efforts to design a framework suitable for most non-core cities, significant differences exist in development paths, historical contexts, and resident preferences. Some generic indicators, such as patent counts or financial inclusion, may not adequately reflect the unique strengths or actual needs of individual cities. Second, the explainability of certain indicators may vary across non-core cities. For example, nighttime light intensity or online visibility, used to represent social vitality, can be distorted by geographic location or administrative boundary definitions, and may fail to accurately reflect socio-economic activity in these cities. Finally, soft aspects of liveability, such as subjective well-being, sense of community, and perceived safety, cannot yet be included due to current data limitations (Mouratidis, 2020). Nevertheless, the indicator framework established in this study provides a robust and comprehensive foundation for depicting the overall liveability profile and internal heterogeneity of non-core cities in China, offering valuable insights for further mechanism exploration and policy development.

Evaluating urban liveability. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used as a reliable and effective method for evaluation. It essentially compares a city's performance in a particular aspect (in this case, liveability) with the best and worst performances of all cities in the same aspect and then uses the distance between them to evaluate the overall performance of the city in an intuitive way (Chen et al., 2018). Based on the indicator system, the TOPSIS method is employed in four steps to evaluate the urban liveability performance of each city:

Step 1: Data collection and normalisation: The data from 237 non-core Chinese prefecture-level cities are collected to form a matrix $\boldsymbol{X} = \left(\boldsymbol{x_{ij}}\right)_{\boldsymbol{mn}}$. Here, $\boldsymbol{i} = \boldsymbol{1, 2, \ldots, m}$, represents a list of $\boldsymbol{m}$ cities; $\boldsymbol{j} = \boldsymbol{1, 2, \ldots, n}$, represents a list of $\boldsymbol{n}$ indicators ($\boldsymbol{m} = \boldsymbol{237}, \boldsymbol{n} = \boldsymbol{21}$). Positivity and negativity of these indicators are determined (Table 1). A positive indicator means that the higher its value, the more it contributes to the liveability of the city, also known as the "best ideal solution", and vice versa.

$$X = \left(x_{ij}\right)_{m\times n} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m1} & \cdots & x_{mn} \end{pmatrix}$$

Step 2: Identifying best/ least ideal solutions: Since the data have been normalised, the maximum value of each indicator in matrix $\boldsymbol{X} = \left(\boldsymbol{x_{ij}}\right)_{\boldsymbol{mn}}$ are the best ideal solutions, noted as aggregate $\boldsymbol{X^+}$. Correspondingly, the least ideal solutions are noted as aggregate $\boldsymbol{X^-}$.

$$X^+ = \left(X_1^+, X_2^+, \ldots, X_n^+\right)$$

$$X^- = \left(X_1^-, X_2^-, \ldots, X_n^-\right)$$

Step 3: Evaluating liveability performance: On this basis, the performance of city i in the jth indicator is calculated:

Distance from the positive ideal solution:

$$D_{ij}^+ = \sqrt{\left(X_{ij} - X_j^+\right)^2}$$

Distance from the negative ideal solution:

$$D_{ij}^- = \sqrt{\left(X_{ij} - X_j^-\right)^2}$$

TOPSIS-evaluated performance of city i in the jth indicator:

$$Performance_{ij} = \frac{D_{ij}^-}{D_{ij}^+ + D_{ij}^-}$$

The matrix $\boldsymbol{Y} = \left(\boldsymbol{Performance_{ij}}\right)_{\boldsymbol{mn}}$ represents the evaluate results of the livability performance of Chinese non-core cities. The results of this evaluation are used to examine whether each type of city has distinguishing characteristics in terms of urban livability and, ultimately, to discuss the connection with different characteristics on urban carbon emissions.

$$Y = \left(Performance_{ij}\right)_{m\times n} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{m1} & p_{m1} & \cdots & p_{mn} \end{pmatrix}$$

Step 4: Weighting indicators: The entropy weighting method is employed to determine the weight of each indicator. This is assigned different importance based on the degree of differentiation and dispersion of the data, and scholars often argue that the higher the degree of dispersion, the more information it contains and the higher the corresponding weight (Zhu et al.,

Table 1 Evaluation framework and representative indicators of urban liveability in Chinese non-core cities.

Dimensions of liveability		Representative indicators	Data source	Weight	Reference
Urban size	**U1:** Population concentration	Population	Yearbook (NBS, 2021)	0.049503	(Pacione, 1990)
	U2: Economic strength	GDP	Yearbook (NBS, 2021)	0.084781	(Pacione, 1990)
	U3: Space for development	Urban built-up area (total)	National Land Survey (MNRC, 2022)	0.073696	(Martino et al., 2021)
Housing and living environment	**H1:** Housing affordability (-)	Ratio between house prices and income	Collected from m.anjuke.com, 2021	0.006006	(Badland et al., 2014)
	H2: Housing supply	Average housing area	Yearbook of Urban Construction (MHRUD, 2021)	0.019821	(Badland et al., 2014)
	H3: Housing environment	Urban green area	Yearbook of Urban Construction (MHRUD, 2021)	0.035429	(Zhao et al., 2021)
Social vitality	**S1:** Daily life vitality	Nighttime light strength	Harvard Dataverse (Wu et al., 2021)	0.110561	(Du et al., 2021)
	S2: Cultural vitality	Library books	Yearbook (NBS, 2021)	0.093111	(Loach et al., 2017)
	S3: Informational visibility	Baidu index	Collected from index.baidu.com, 2019	0.049258	(Du et al., 2024b)
Innovation capacity	**I1:** Practical innovation	Patents	Collected from CNKI, www.cnki.net, 2020	0.107640	(Liu et al., 2020)
	I2: Education for innovation	Teachers of higher education	Yearbook (NBS, 2021)	0.053517	(Peng & Xu, 2024)
	I3: Innovation support	Governmental expenditure for scientific research	Yearbook (NBS, 2021)	0.046406	(Xiong et al., 2020)
Employment condition	**E1:** Potential of employment	Large enterprises number	Yearbook of Urban Construction (MHRUD, 2021)	0.131568	(Yan, 2021)
	E2: Income of employment	Salary level	Yearbook (NBS, 2021)	0.004463	(Wang & Shao, 2022)
	E3: Entrepreneurial environment	Financial inclusion index	Digital Finance Research Centre at Peking University (Guo et al., 2020)	0.018753	(Guo et al., 2020)
Urban greenness	**G1:** Environment quality (-)	PM 2.5	ChinaHighPM2.5 (Wei et al., 2020)	0.022696	(Ji et al., 2020)
	G2: Ecology quality	NDVI index	National Ecosystem Science Data Centre	0.007355	(Ji et al., 2020)
	G3: Energy efficiency (-)	Carbon intensity	The Emissions Inventories for 290 Chinese Cities (Shan et al., 2022)	0.004499	(Shan et al., 2022)
Public good	**P1:** Social welfare guarantee	Pension insurance for employee	Yearbook (NBS, 2021)	0.038949	(Lan et al., 2020)
	P2: Basic education support	Teachers for primary school	Yearbook (NBS, 2021)	0.020817	(Zhan et al., 2018)
	P3: Urban infrastructure	Urban road length	Yearbook (NBS, 2021)	0.021170	(Zhan et al., 2018)

(-) means negative factors.

2020). The decision-making effectiveness of TOPSIS is also enhanced through the entropy weighting method (Chen, 2021). This is calculated as follows:

$$E_j = -\frac{\sum_{i=1}^{m} r_{ij} \ln r_{ij}}{\ln(m)}$$

Where $\boldsymbol{E_j}$ means the entropy value, $\boldsymbol{r_{ij}} = \frac{p_{ij}}{\sum_{i=1}^{m} p_{ij}}$, $\boldsymbol{p_{ij}}$ means the performance of city $\boldsymbol{i}$ in the $\boldsymbol{j}$**th** indicator, and $\boldsymbol{m}$ means the total amount of cities. And the weight of **jth** indicator $\boldsymbol{W_j}$:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^{n} \left(1 - E_j\right)}$$

Exploring relationships between carbon emissions and liveability. This study proposes a novel perspective for analysing heterogeneity through the typological classification of non-core cities. For further exploration, it employs Spearman correlation analysis to examine the general relationship between carbon emissions and liveability, while also assessing the relative importance of each liveability dimension in shaping the overall liveability performance. In parallel, the Coupling analysis is introduced to evaluate the degree of carbon dependency across different liveability dimensions. Together, these approaches provide an empirical foundation for summarising the distinct carbon-liveability dynamics across city types, thereby informing the optimisation of decarbonisation policy pathways tailored to local urban contexts.

Spearman's correlation coefficient is used to measure the monotonic relationship between variables (Myers & Sirois, 2014), as a non-parametric method, it does not assume linearity or normal distribution, making it well-suited and more flexible for urban liveability data. By calculating the Spearman coefficient between each liveability indicator and the composite liveability score, we quantify the relative importance of individual indicators across different types of non-core cities. A higher coefficient suggests a stronger contribution of that dimension to perceived liveability.

On the other hand, to assess the carbon dependency of each liveability dimension, we adopt Coupling analysis commonly used in the exploration on the relations among multiple urban systems (Shen et al., 2018). This model captures the interaction intensity between two systems, in this case, carbon emissions ($\boldsymbol{X}$) and a liveability performance ($\boldsymbol{Y}$):

$$\boldsymbol{C} = \frac{2 \cdot \sqrt{X \cdot Y}}{X + Y}$$

Both $\boldsymbol{X}$ and $\boldsymbol{Y}$ are normalised data, and $\boldsymbol{C}$, representing coupling degree, ranges from 0 to 1, with higher values indicating stronger interdependence: a high coupling degree means that improvements in that liveability dimension tend to occur alongside higher carbon emissions.

Results

Four types of non-core cities and the disparities in liveability. The Silhouette method is applied to determine the number of target types in K-means clustering analysis, that is, the predefined value of K, which has also been widely validated as an effective and reliable method (Han, 2022; Oprea & Bâra, 2024). Accordingly, four types of non-core cities are identified based on the composition of the carbon emissions, and the result is visualised in two dimensions using the Principal component analysis method (Fig. 2), presenting no overlap of cities in the four types. This study first geospatially maps these cities by typology to get a first impression of the characteristics of these types (Fig. 3).

Among them, Type 3 ($n = 141$) contains the largest number of cities. Most of them are highly industrialised cities, especially in heavy industrial sectors. Some cities of this type are undergoing industrial transformation to move towards a more advanced economic structure. Cities in the southeast coastal region, for example, have benefited from the progress of globalisation and regionalisation and have further upgraded their manufacturing industries to integrate into and profit from the global market. Type 1 ($n = 10$) contains the smallest number of cities. Most of them are smaller-sized cities. The spatial distribution of these cities is also mainly in the peripheral areas of the province. Type 2 ($n = 36$) and Type 4 ($n = 50$) are not easy to distinguish at first glance. Overall, the economic and industrial situation of these two types of cities falls between Type 3 (highly industrialised) and Type 1 (underdeveloped).

Carbon emissions per capita and overall liveability performance are also measured to compare different types (Fig. 4). The results validate differences among types in the first impression. Type 3 produces much higher emissions than the other types in industry, transportation, and energy, illustrating the better industrial development. Type 1, on the other hand, has the lowest emissions in almost all dimensions, especially industry and energy, suggesting that these cities are lagging behind in heavy industries. The difference between Type 2 and Type 4 is also evident: Type 2 has significantly higher per capita carbon emissions than Type 4 and is more like a "smaller version" of Type 3, as Type 2 also has higher emissions from industry, transport, and energy.

To sum up, Type 1 are very small cities with a low level of industrialisation and are also at the periphery of the regional economic system. Type 2 are cities in the process of industrialisation and are mostly moderately developed, the liveability is only second to Type 3. Type 3 are the most industrialised cities, with the highest level of carbon emissions in the dimensions of industry, transport and energy. Finally, Type 4 has the highest per capita carbon emissions from services and agriculture. This also characterises these cities as less developed, service-oriented cities with low liveability.

Disparities of multidimensional liveability. This study further calculates the performance of each type on various liveability dimensions (Fig. 5). Type 3 has the best performance in almost all dimensions, except for housing and urban greenness. This is not surprising, as the development of heavy industries brings more wealth, but excessive carbon emissions also affect the urban environment and greenness, while the development of socio-economics further leads to housing shortage and overpricing. In contrast, Type 2, while being industrialising cities, performs well in these two dimensions, and scores well in innovation, employment, and social vitality. Type 1 and Type 4 are less fortunate. These cities lack social vitality, innovation, and a good employment environment, and are only favourable in the urban greenness because they do not have a mature industrial system and suffer less from carbon emissions and pollution. Notably, Type 1 cities are very small, but have sufficient public good. Based on this, disparities in the liveability of each type are explored further.

Type 1: Underdeveloped cities in the regional periphery. The most remarkable characteristic of Type 1 is the optimal performance of these cities in Energy efficiency (G3) (Fig. 6). Moreover, this type also performs well in the Environment and Ecology quality (G1 & G2), considerably better than Type 3. However, this group of cities is poor in several other dimensions, particularly in Social vitality and Innovative capacity. The nighttime lighting index

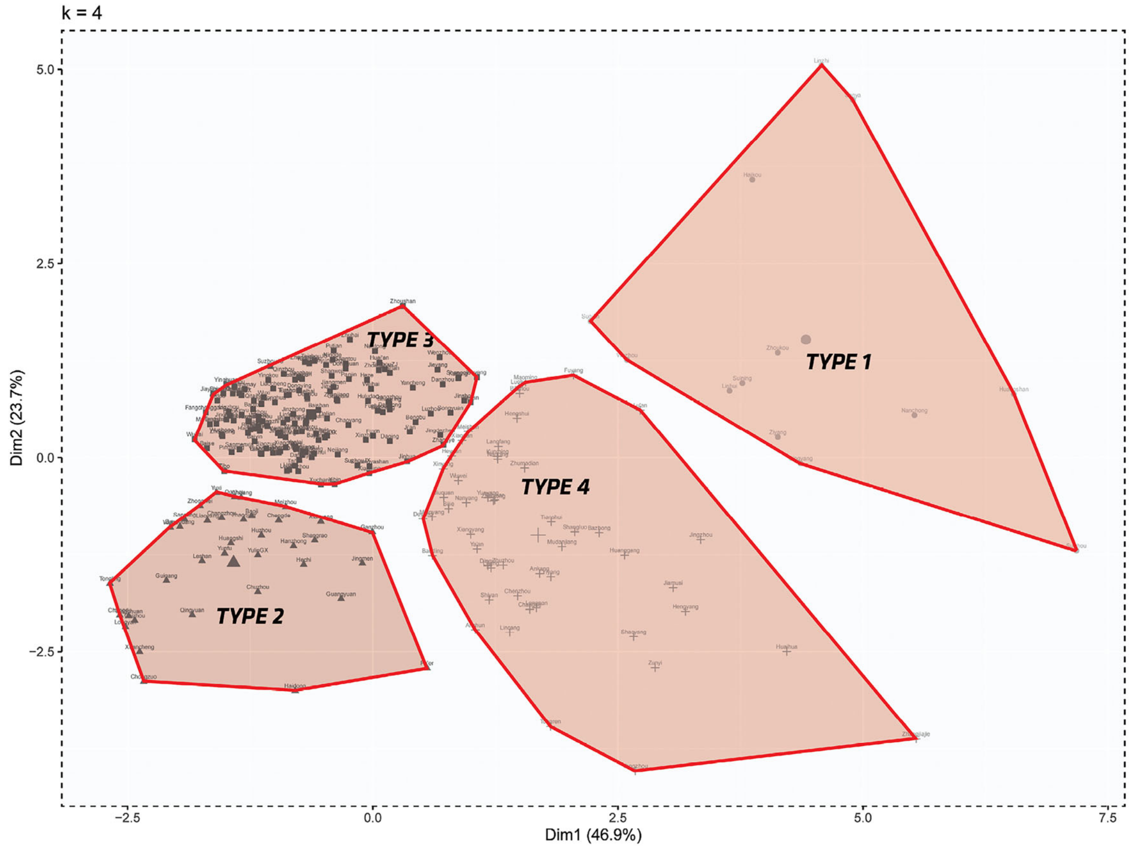

Fig. 2 PCA visualisation of four types of non-core cities.

proves that the Daily life vitality (S1) in these cities is lower than in Type 2 and Type 3, while they are also among the worst performers in Practical innovation (I1) and in Education for innovation (I2). Such weaknesses in social and innovation are further reflected in the Employment condition, where all three aspects perform poorly. This indicates that these cities do not have a sufficient number of quality jobs, nor do they have an open and inclusive market environment to stimulate entrepreneurial activities. Scholars have also discussed these problems in recent years. For example, the socio-economic unevenness between the three non-core cities of Ziyang, Nanchong, and Suining, with their neighbouring mega-metropolises of Chengdu and Chongqing, is considered as an important limiting factor towards the future coordination and sustainability of the region (Du et al., 2024b). In general, the cities of Type 1 show a weak industrial base and a lagging urban socio-economic development, which can be confirmed by their comparatively low proportion of carbon emissions from industry and their poor performance in economic terms. Along with this, the city's Social vitality, Innovative capacity, and Employment environment pose significant challenges to their urban liveability. The city's outstanding Urban greenness may be a compensation for these shortcomings.

To summarise, Type 1 cities are at a relatively backward level of economic development. Meanwhile, the low performance in the dimensions of social vitality, innovation, and employment is also indicative of the city's lagging behind, which can be attributed to the lack of well-developed urban industrial systems. On the positive side, the cities show promising performance in urban greenness and public good.

Type 2: Small cities with promising socio-economic lives. Type 2, as a cluster of non-core cities that does not stand out in size, has strong performance in other factors of liveability (Fig. 7). It is the best performer in the dimension of Housing and living environment and is second only to Type 3 in the Innovation capacity. This suggests that these cities value the importance of innovation and knowledge, also proven by previous studies: the cities in Southern Anhui, which are located on the periphery of the Yangtze River Delta and are often considered to be poorly integrated into the mega-regional networks. In response, some cities in this region have taken advantage of their own innovation capabilities and hope to form a more competitive cities alliance (Xiong et al., 2017). Regarding the dimension of Employment condition, these cities have a comparable number of large firms as Type 3 (and significantly smaller populations), which can explain their highest Income of employment (E2), and the higher performance in Entrepreneurial environment (E3). This type includes more socio-economically developed cities like Changzhou and Wuhu that play an important role in the regional economic network, and scholars have also identified the rise of entrepreneurship in smaller cities included in this type (Chen & Su, 2022). Besides, Type 2 has the best performance in both Environment quality (G1) and Ecology quality (G2). Despite not being outstanding in population and economy, some of these cities are renowned tourist cities because of the rich natural landscapes and cultural resources (Xu & Dong, 2022).

Overall, Type 2 cities are the smallest in population size, but they have (or are pursuing) the same well-developed industrial systems as Type 3, which is reflected in the higher industrial and energy emissions in this type of city. As a result, Type 2 achieves satisfactory liveability, winning in terms of social vitality, innovation, and employment with the smallest population. Housing in these cities also does not face serious challenges regarding supply, price, and quality compared to Type 3.

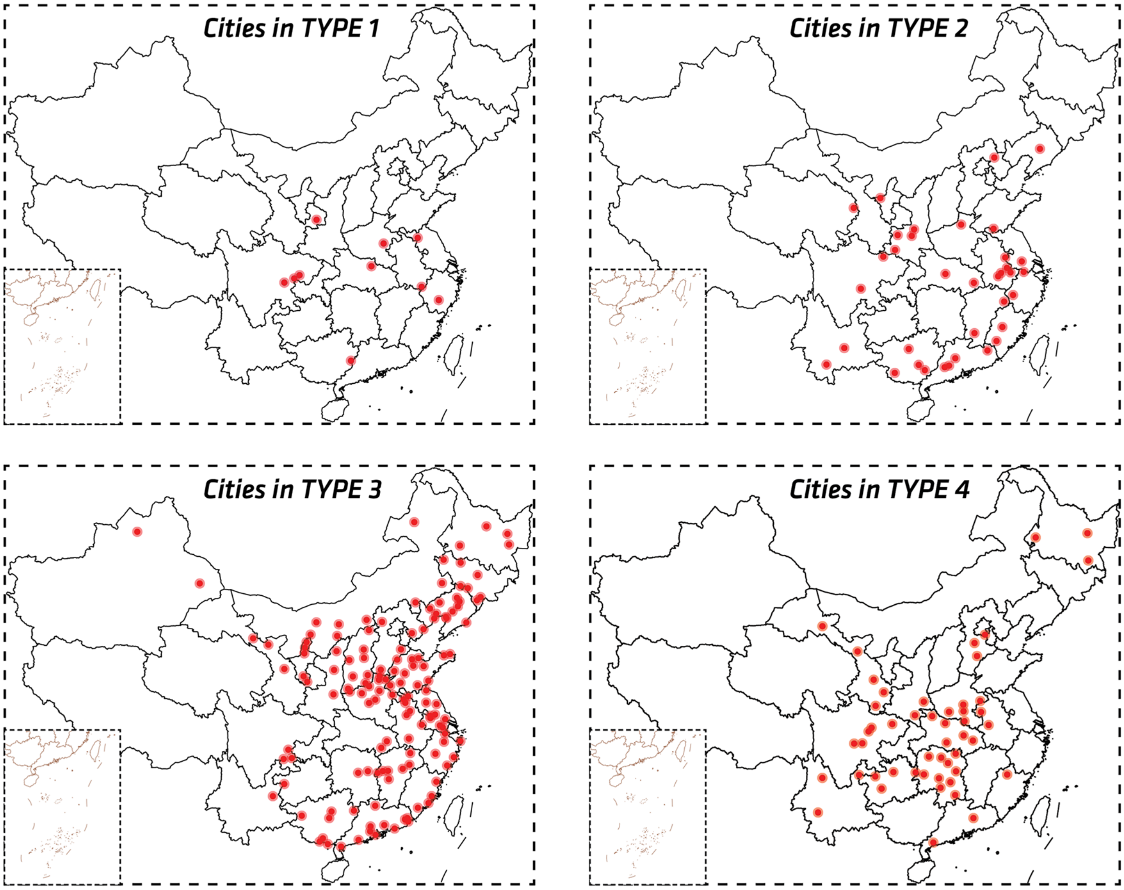

Fig. 3 Geospatial location of four types of non-core cities.

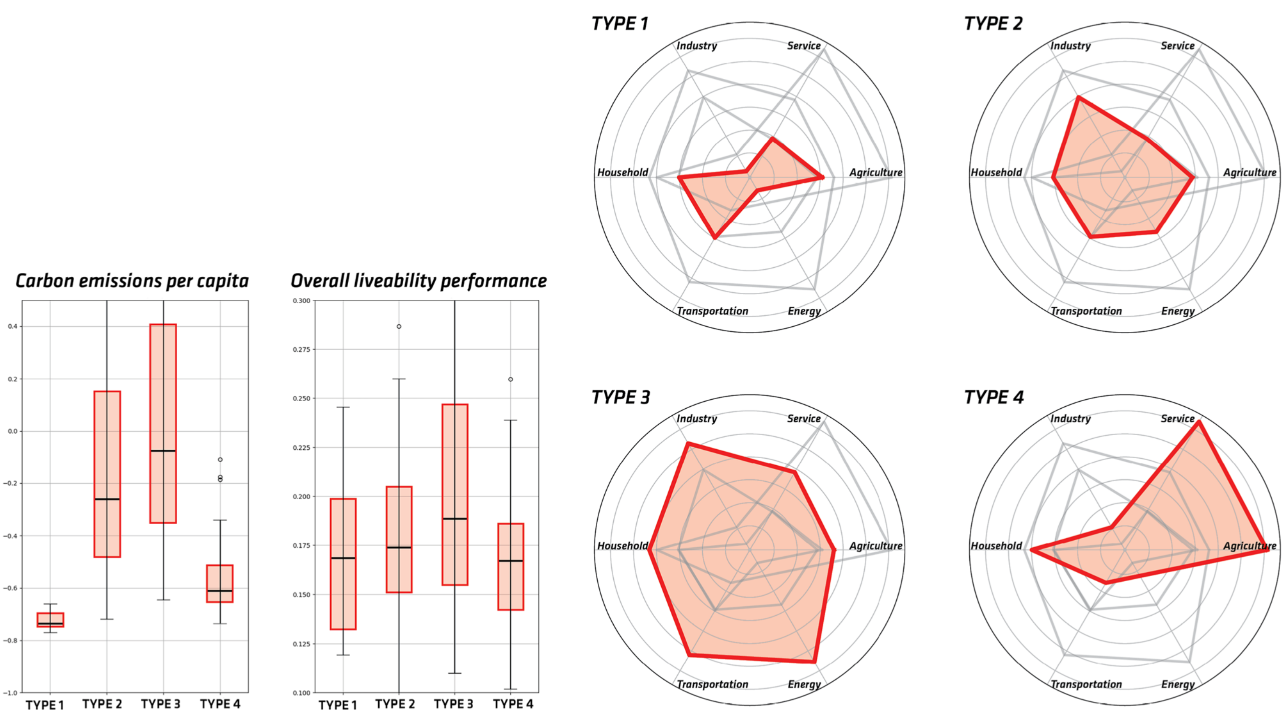

Fig. 4 Comparing carbon emissions of four types of non-core cities.

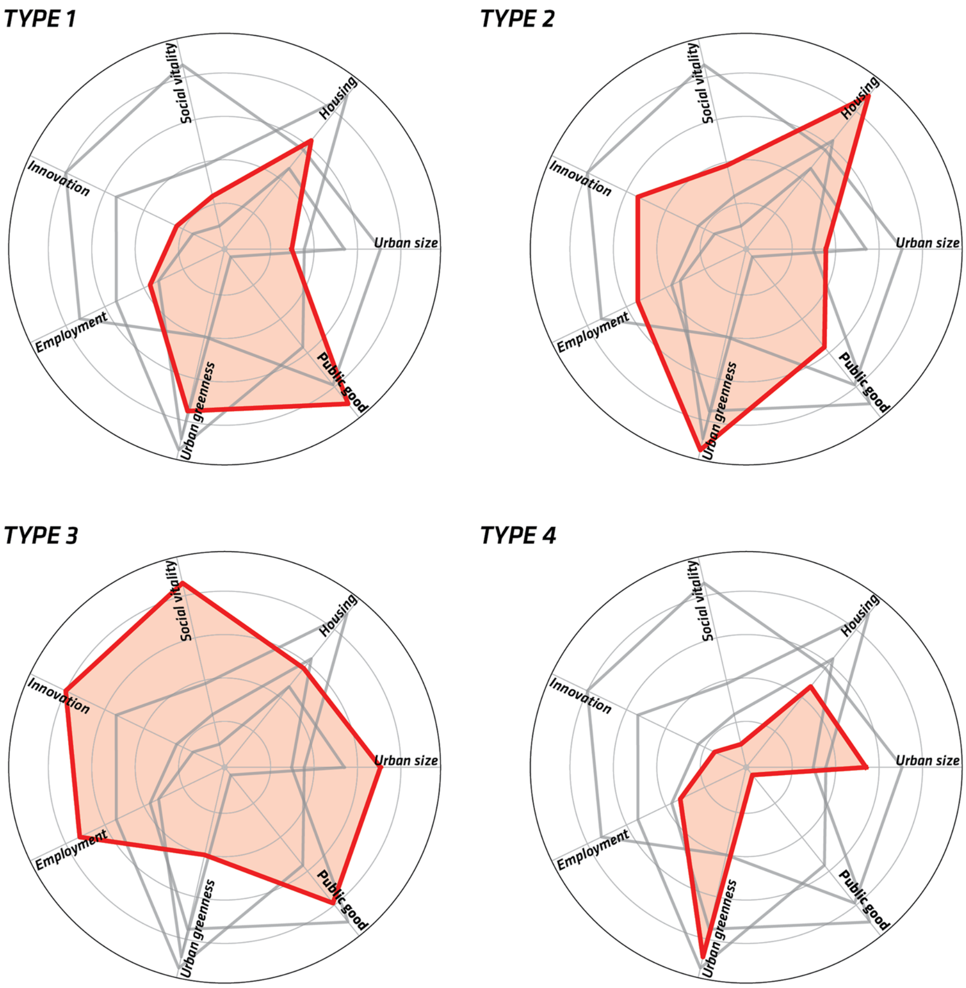

Fig. 5 Comparing the multidimensional liveability of four types of non-core cities.

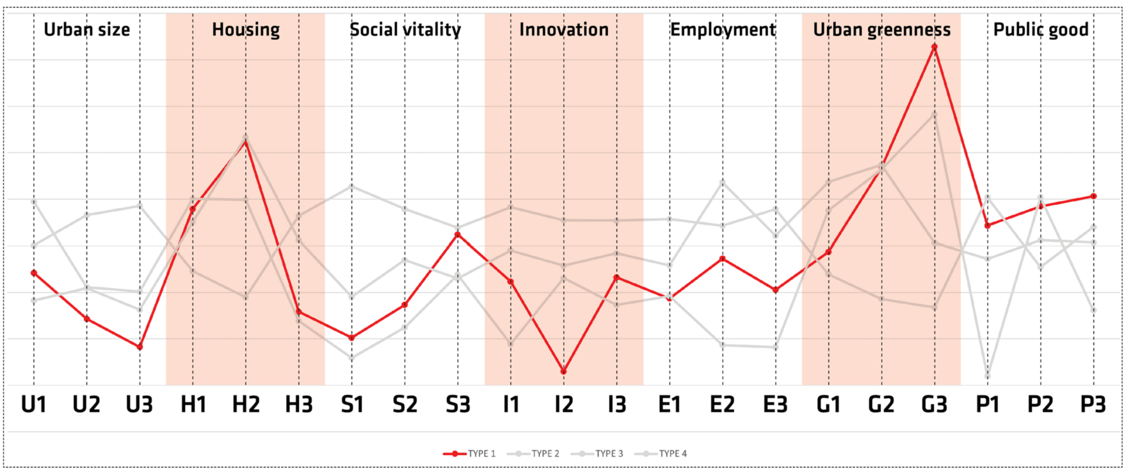

Fig. 6 Liveability performance of Type 1.

Type 3: Highly industrialised cities with larger size. Type 3 is highly notable for the largest Economic strength (U2), Space for development (U3), and a relatively large population (Fig. 8). The total amount of carbon emissions is also much higher than other types. Such high-carbon emissions may be the price of the strongest liveability. This is obviously correlated with the strong economy: they are basically highly industrialised and play a key role in the regional economic networks. For example, some cities located in the Yangtze River Delta, such as Suzhou, have long been considered the most developed cities owing to their advanced industrial clusters and open market governance capacity (Wang et al., 2015). Meanwhile, more than half of Type 3's cities are clustered in northern China, including the Loess Plateau, North China Plain, and Northeast China. These regions have been important sources of coal and steel production for decades. For example, Handan and Tangshan, located in the

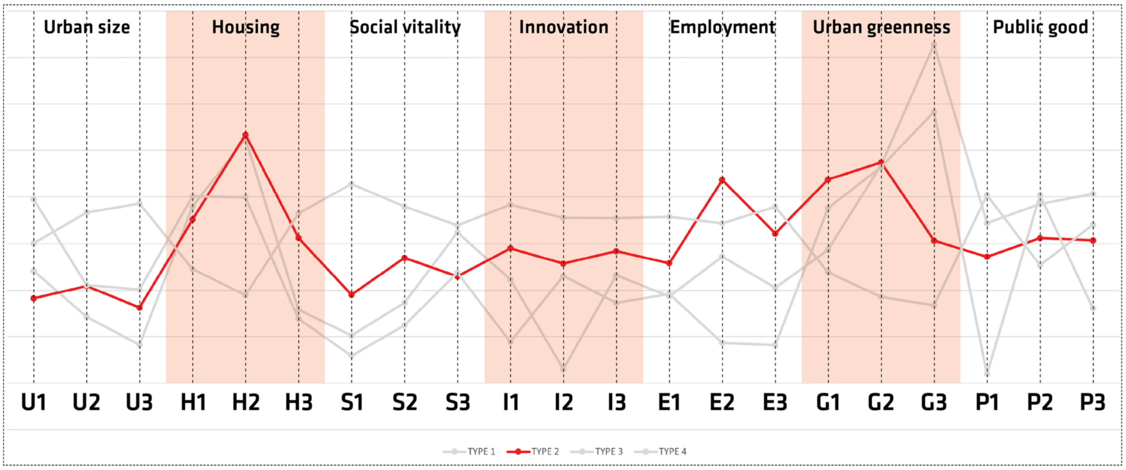

Fig. 7 Liveability performance of Type 2.

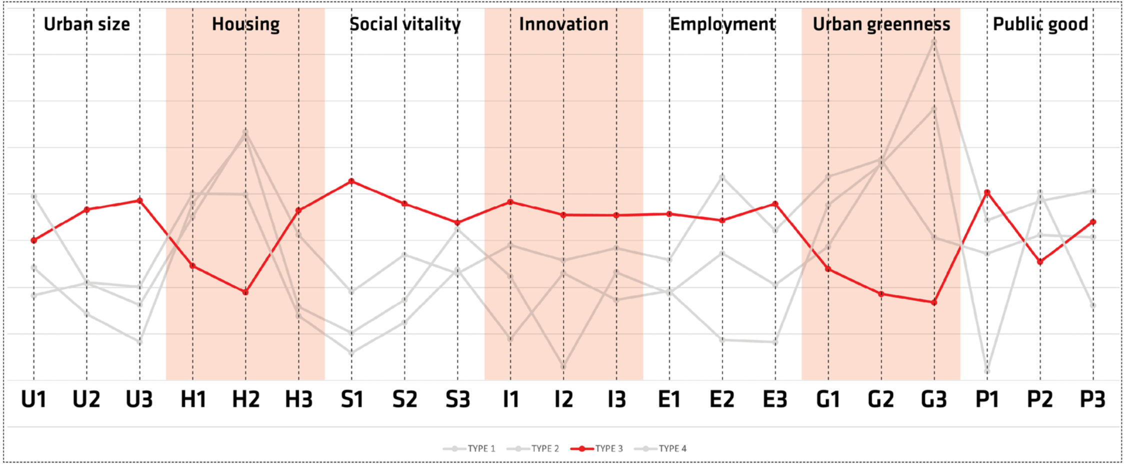

Fig. 8 Liveability performance of Type 3.

Beijing-Tianjin-Hebei mega-region, are responsible for nearly one-fifth of the country's steel output (Yang et al., 2019). Moreover, we find that the good performance of the liveability of such industrially developed cities comes at the cost of environmental and ecological degradation: cities of this type have the worst performance in terms of both Environment and Ecology quality (G1 & G2).

Type 3 gathers the largest number of cities and is the result of the national development trajectories promoted by Chinese authorities towards industrialisation in the last decades. This has long been considered an important driver of Type 3's better liveability performance, but at the same time, it also proves to be costly in the dimensions of housing and greenness, which should also be important issues for Type 3 as it enters into the advanced industrialisation stage, e.g., the stability of the real estate market and the transformation of the economic system of the resource-based city are often considered to be the most important ways for future sustainable growth (Garriga et al., 2023).

Type 4: Populous cities struggling with low liveability. Although Type 4 is significantly lower than Type 3 regarding Economic strength (U2) and Space for development (U3), these cities have the largest populations and struggle most regarding liveability (Fig. 9). Such a large population size does not bring these cities better urban liveability in almost all other dimensions. First, they perform poorly in the Housing and living environment dimension. Such problems have triggered the attention of local authorities in some cities. For example, Langfang's housing prices have grown abnormally in recent years because of its location adjacent to Beijing, and the responding governance and regulation have shown limited effectiveness (Li et al., 2020). On the Innovation capacity, these cities have a moderate performance in Education for innovation (I2) and Innovation support (I3), indicating that their governments are to some extent emphasising urban innovation and have a certain base of innovation facilities, including universities and research institutes. However, these resources do not transform into productive innovations, and these cities are the worst performers in Practical innovation (I1). Looking at the other dimension, Urban greenness, TYPE 4 performs better in all categories, especially the Ecology quality (G2).

Overall, Type 4 has the largest population, but it performs the worst on most of the indicators of liveability. We also find that this type has a lower proportion of industrial and energy emissions compared to Type 2 and Type 3, suggesting that the low liveability of these cities seems to arise from the backwardness of their industrial sectors, but this leads to a better performance in greenness.

Exploring the relations between carbon emissions and liveability through typology. Spearman correlation analysis confirms the significant positive relationship between carbon emissions and liveability in Chinese non-core cities, with a correlation coefficient of $\rho = 0.411$ (Fig. 10). This suggests that cities with

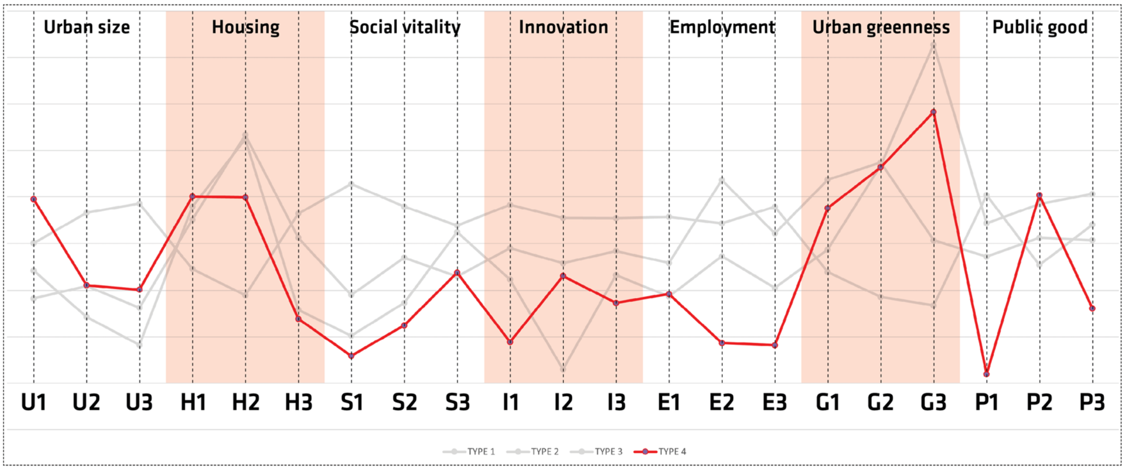

Fig. 9 Liveability performance of Type 4.

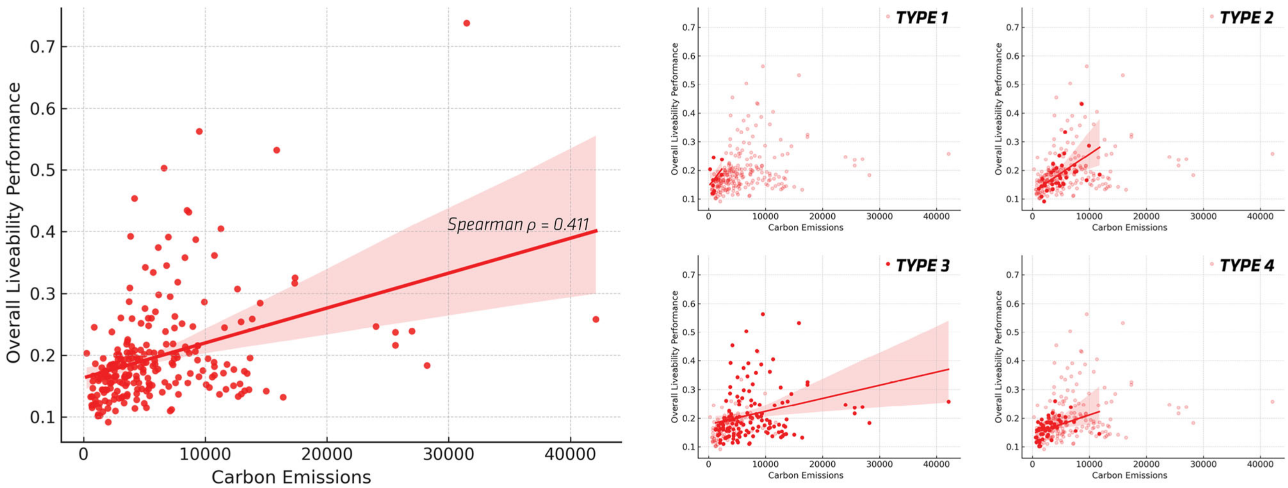

Fig. 10 Positive correlations between carbon emissions and liveability.

higher carbon emissions tend to offer better overall liveability. On one hand, this finding indicates that the improvement of liveability in non-core cities often relies on a series of carbon-intensive socio-economic activities. On the other hand, it also highlights the pressure that decarbonisation policies may impose on non-core cities: under current developmental conditions, lower carbon emissions may imply lower levels of liveability. In other words, the correlation analysis reveals that in non-core cities, the creation of liveability remains highly dependent on carbon emissions.

More importantly, this positive correlation is not incidental but widely observed across all four city types. For Type 1 cities, which are less developed, both carbon emissions and liveability are generally low. This indicates that low levels of socio-economic activity, while associated with low-carbon outputs, also result in unsatisfactory living conditions for residents. Compared to them, Type 2 cities demonstrate relatively higher "carbon efficiency" in terms of liveability performance. That is, for the same level of carbon emissions, these cities can convert carbon-intensive activities into more effective improvements in liveability. Nevertheless, regarding absolute performance, they still lag far behind Type 3 cities, which typically exhibit stronger socio-economic levels. Notably, some Type 2 cities such as Chengde and Sanming may not hold significant economic positions within the regional system, but are widely known for their high-quality ecological environments, active tourism sectors, and well-developed social services (Wu et al., 2023). For Type 3 and 4, where liveability is commonly achieved through carbon-intensive development, striking a balance between decarbonisation and liveability enhancement represents a critical challenge for future urban development.

Building on the correlation exploration, we further employed a coupling analysis to investigate the degree to which each dimension of liveability is dependent on carbon emissions (Fig. 11). Across all four city types, there exists a certain structural consistency in carbon dependence. In particular, dimensions related to Urban Size, notably Population concentration (U1) and Economic strength (U2), as well as indicators like Potential of employment (E2), consistently exhibit high coupling degrees across types (with greater variability observed in Type 1 cities due to limited simples and their lower development levels). This indicates that non-core cities tend to rely heavily on carbon-driven strategies when it comes to fundamental aspects of liveability, such as enhancing urban capacity, stimulating economic dynamism, and ensuring employment.

However, some types reveal sign of decoupling in liveability improvements across several other dimensions, particularly in Housing and Living Environment, Social Vitality, and Public Goods. For instance, in Informational visibility (S3), Type 4 cities demonstrate lower coupling degrees than Type 2 and Type 3. Similarly, Housing affordability (H1) and Housing supply (H2) show weaker carbon dependence in Type 2 and Type 4 cities.

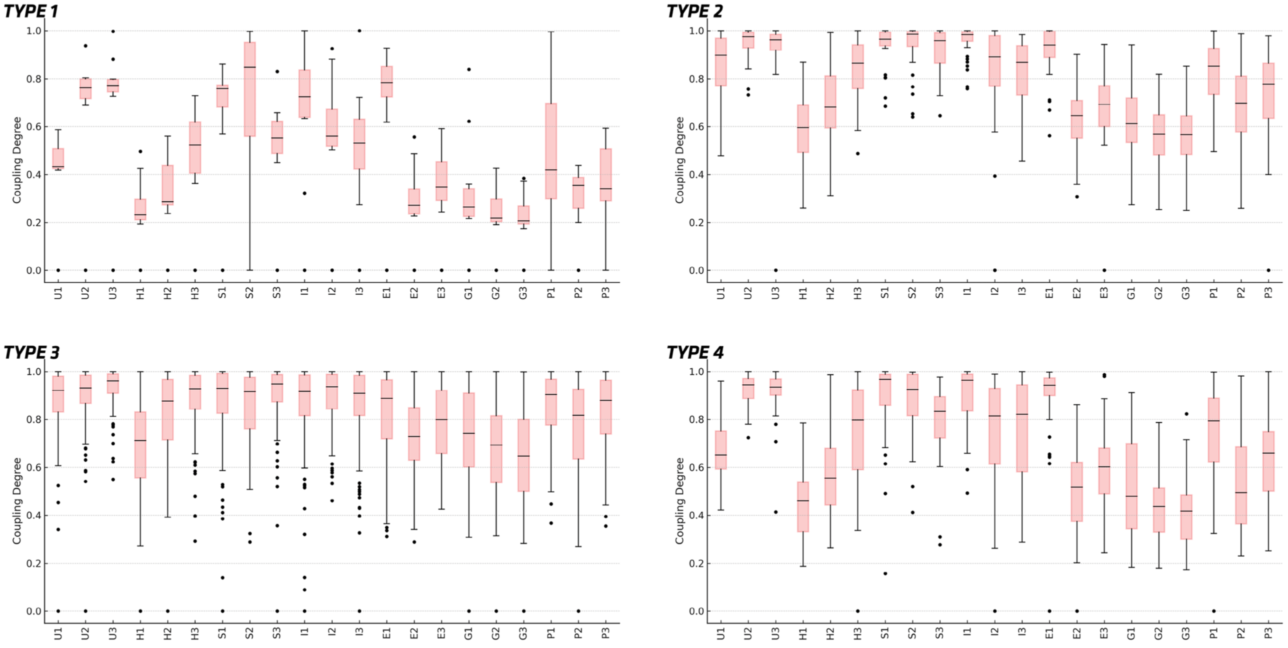

Fig. 11 Coupling analysis between liveability dimensions and carbon emissions.

Also in Basic education support (P2) and Urban infrastructure (P3), these dimensions are marked by considerably higher coupling degrees in Type 3 cities. These contrasts suggest that Type 3 cities still have significant potential for decoupling liveability improvements from carbon-intensive processes, especially in social vitality and housing.

While it is generally expected that improvements in Urban Greenness dimensions, such as Energy efficiency (G1) and Ecology quality (G2), would align with decarbonisation objectives, it is notable that even within these environmentally oriented domains, Type 3 cities still show higher coupling levels. This reinforces the observation that despite their relatively strong liveability performance, Type 3 cities are confronting structural challenges tied to carbon dependency. Tangshan and Zibo, these highly industrialised cities, exemplify the challenges faced by Type 3 cities. They have historically relied on heavy industries such as steel and manufacturing, which not only drive local economic strength and employment potential, but also contribute significantly to their carbon emissions.

On the basis of carbon-liveability coupling (as also represented on the vertical axis in Fig. 11), we further applied Spearman correlation analysis to evaluate the importance of each liveability dimension in shaping overall performance (Fig. 12). This bivariate quadrant matrix enables the identification of the extent to which specific liveability dimensions contribute to overall liveability, while simultaneously revealing their degree of coupling with carbon emissions. An initial step involves examining the similarities and differences in the importance of liveability subdimensions across the four city types. Two indicators, Economic strength (U2) and Space for development (U3), consistently emerge as the most important drivers of liveability in all types of non-core cities. Located in the upper-right area of the scatterplots, these dimensions are not only strongly correlated with overall liveability but are also highly carbon-dependent. This pattern highlights the foundational role of economic activity and spatial growth in shaping liveability, but at a considerable carbon cost. A similar pattern is observed for Potential of employment (E1), suggesting that access to stable job opportunities, often underpinned by the presence of large enterprises, remains a fundamental pillar of people's daily life. In Type 2, 3, and 4, dimensions related to Social vitality and Innovation capacity, especially Daily life vitality (S1) and Practical innovation (I1), also display high importance and carbon coupling. Moreover, in Type 2 and Type 3 cities, we see additional emphasis on Housing environment (H3) and Social welfare guarantee (P1). These dimensions demonstrate notable carbon dependency, though their contribution to overall liveability is comparatively modest. In Type 4 cities, the coupling degree of these same indicators is significantly lower.

On the other hand, several indicators consistently show low importance in shaping overall liveability across all city types. These include Innovation support (I3), Housing affordability (H1), and Basic education support (P2). One possible explanation is that these are areas in which most cities have already made substantial investments in a more balanced way, thus leading to a diminished marginal impact on perceived liveability. In the case of housing affordability, the challenge of high housing costs is pervasive across urban China, regardless of city types. As shown in Supplementary Material 1, H1 is negatively correlated with other important liveability dimensions such as social vitality and innovation capacity, suggesting that housing cost pressures may actually undermine other aspects of liveability rather than enhancing them.

The mapping suggests that Type 2 cities generally demonstrate a relatively balanced pattern, where high-carbon indicators tend to contribute more meaningfully to liveability, and vice versa. In contrast, Type 3 cities show high-carbon coupling across almost all dimensions, confirming a structurally carbon-intensive model of development again. Type 4 cities include several indicators that exhibit high-carbon dependency but low contribution to liveability.

The analysis reveals several key insights into the relationship between carbon emissions and urban liveability in Chinese non-core cities. First, a strong positive correlation suggests that cities with higher carbon emissions tend to offer better overall liveability, highlighting the current reliance on carbon-intensive socio-economic activities for urban development. This reliance poses a challenge for advancing decarbonisation without compromising residents' quality of life. Second, distinct patterns emerge across different city types: Type 1 cities remain

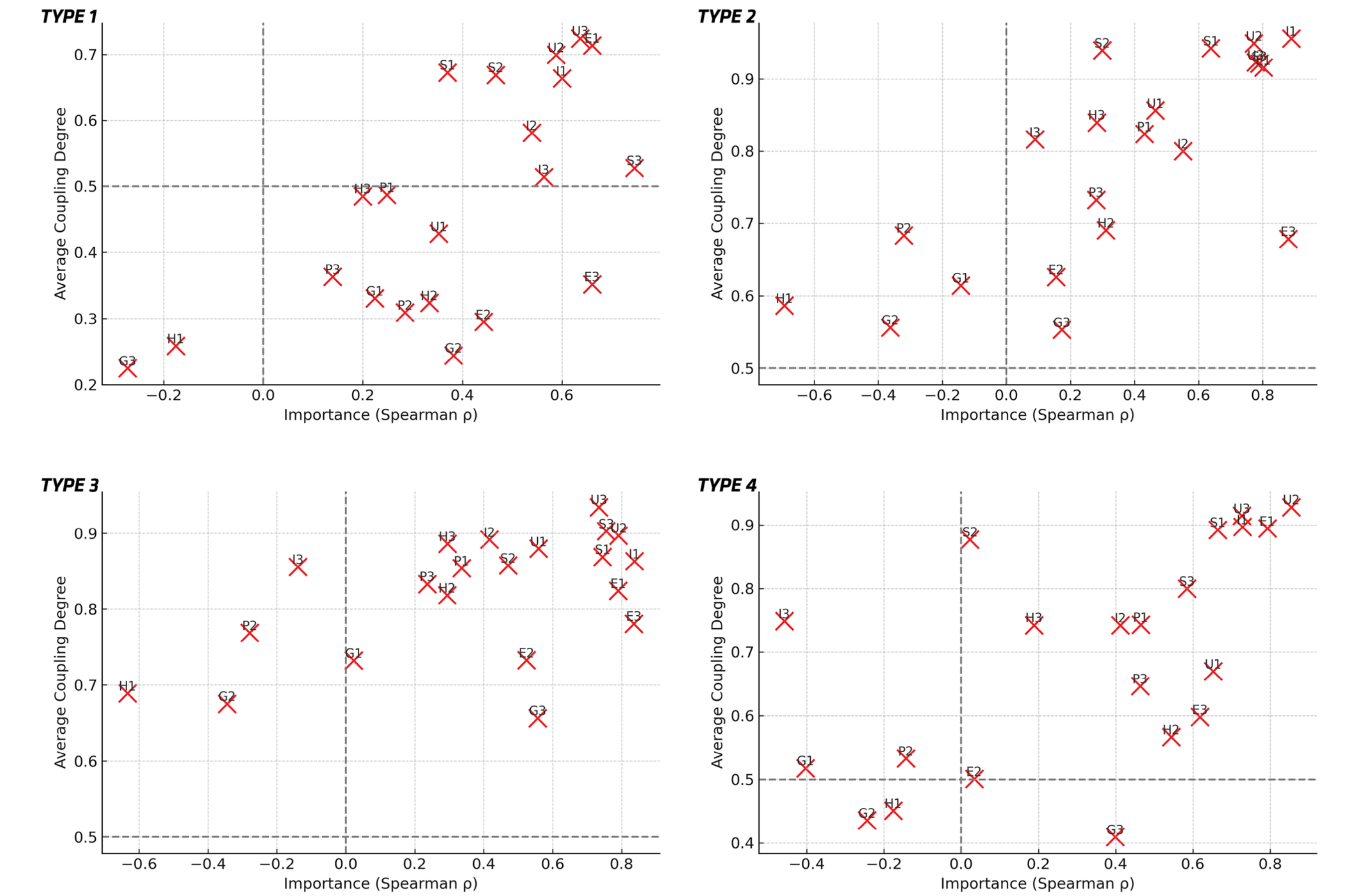

Fig. 12 Mapping importance of liveability dimensions and the coupling with carbon emissions.

underdeveloped with both low emissions and low liveability; Type 2 cities demonstrate relatively better "carbon efficiency", converting emissions into liveability more effectively; Type 3 cities exhibit strong liveability performance but are heavily dependent on carbon across nearly all dimensions; while Type 4 cities occupy an intermediate position, with some high-carbon investments yielding limited improvements in liveability. Third, indicators such as Economic strength (U2), Space for development (U3), and Potential of employment (E1) are consistently the most important contributors to liveability but are also highly coupled with carbon emissions, reflecting a common reliance on expansionary and resource-intensive urban growth models. Meanwhile, other dimensions like Informational visibility (S3), Housing affordability (H1), and Basic education support (P2) show weaker carbon dependence, particularly in Type 2 and Type 4 cities, suggesting opportunities for more sustainable pathways. These findings underscore the need for differentiated and targeted policy strategies that account for city-specific characteristics in both emissions structure and liveability demands.

Discussion

This research pioneers a typological exploration of the connection between carbon emissions and various dimensions of liveability. In this way, a comprehensive portrait of the four different types of cities is drawn regarding their carbon emission components, and subsequently reveals distinguishable performances of liveability. Accordingly, it is obvious that cities with high total carbon emissions tend to have high overall liveability, and vice versa. This aligns with previous studies, scholars have revealed the struggling role of small cities in the decarbonisation process (Chen et al., 2023). The classification of types is based on the composition of different carbon components and not only on the combined total. This leads to the argument that higher carbon emissions correlate with higher liveability because of industrialisation, triggering more emissions regarding industries, energy, and transportation.

The relationship between carbon emissions and urban liveability confirms a broader structural pattern: the advancement of industrialisation has laid the foundation for liveability in many non-core cities, while simultaneously embedding them in a development paradigm heavily reliant on carbon-intensive socio-economic activities. The strong positive relationship between carbon emissions and liveability does not imply that "more carbon is better", but rather highlights that current pathways to liveability improvement in non-core cities remain largely dependent on carbon-intensive approaches. The first approach is an urban expansion-oriented pathway based on economic activity and spatial agglomeration. Core contributors to urban liveability, such as employment opportunities, entrepreneurial environment, population concentration, and land development, are consistently among the most influential factors across all city types. The second is an attraction-oriented pathway that emphasises maintaining urban vitality. This includes fostering innovation, improving daily life convenience, and cultivating a dynamic social and cultural atmosphere. These activities often entail significant indirect carbon emissions, driven by increased consumption or transportation demand. The third is a basic service-oriented pathway, where perceived liveability in residents' daily lives is shaped by the availability of infrastructure, social welfare systems, or public amenities. In non-core cities, however, such systems are typically delivered through conventional, resource-intensive interventions due to limited access to technologies (such as digitalisation) and institutional capacity, making them particularly carbon-dependent.

On the other hand, the typological exploration also sheds light on the heterogeneity of the carbon-liveability relationship in non-core cities. For instance, Type 1 cities are characterised by both low-carbon emissions and low overall liveability, indicating that foundational development in areas such as employment, infrastructure, and population attraction is still lacking. Type 2 cities remain at a modest stage of development compared to Type 3, they exhibit relatively high "carbon efficiency" in liveability. Notably, these cities show lower carbon dependence in dimensions such as innovation capacity, housing supply, and informational visibility, while performing well in ecological and social service domains. Type 3 cities exhibit high overall liveability but remain strongly dependent on carbon across nearly all liveability dimensions. This suggests a structurally carbon-intensive development model, where economic strength, spatial expansion, and employment potential are all heavily coupled with carbon emissions. Type 4 cities generally fall in the upper-middle range for both carbon emissions and liveability, but show discrepancies where certain high-carbon investments (e.g., in housing or social welfare) yield limited liveability improvements.

Policy recommendations have been widely discussed and put forward to address the most significant factors associated with carbon emissions, urban size and industrial development (Zhu et al., 2022). However, for non-core cities, a big challenge in pursuing decarbonisation may lie in the fact that it often comes at the expense of liveability. Studies show that in European countries such as Germany and Denmark, compulsory policies to control carbon emissions are often accompanied by a deterioration of the employment environment (Kopidou et al., 2016). In Brazil, this high dependence on carbon emissions for socio-economic activities is even more severe because the government's encouragement of heavy industries and prioritisation of profitability (Rüstemoğlu & Andrés, 2016). Although Chinese socio-economic activities are beginning to show a trend of shifting away from high-carbon emissions in some major cities, underpinned by policy constraints on industrial development (Du et al., 2021), this study questions such progress at the level of non-core cities. Therefore, the characterisation of the different carbon emissions and the urban liveability associated with them should be used as a reference for policymaking rather than only considering the carbon reduction goals of a particular economic or industrial sector or applying the same goal to all cities.

Given that Type 2 and Type 3 are more optimistic about liveability, policies can be stricter to encourage the introduction of new industries and restructuring of the economic system, thus realising the vision of decoupling urban liveability and carbon emissions. For Type 3, the upgrading of the industrial structure is urgent, as these cities already have a well-developed industrial base and a more advanced liveability, which allows them to appropriately restrict the development of high-pollution, high-energy-consumption, and labour-intensive industries, so as to encourage the cultivation of emerging economic sectors. Type 2, as smaller cities undergoing industrialisation, needs more policy support and guidance to facilitate its progress towards a more advanced economic structure while controlling the transformation of heavy industry, including funds for innovation and research, and policy support for investment attraction.

For Type 1 and Type 4, which have relatively poor liveability, carbon emissions policies need to consider more about the quality of life for the local residents, so as to avoid overly aggressive carbon reduction actions that would put more burden on these cities and further undermine their limited liveability. For example, Type 1 has poor industrial development and low liveability, so economic stimulation policies are necessary, such as directing external industries and investments to the city and supporting local enterprises. In addition, these cities are on the periphery of the region, so establishing greater cooperation with the other bigger cities could help them better integrate into and benefit from the regional system. Type 4 is the most problematic, with the largest population, but struggling with a low level of liveability. However, carbon emissions from agriculture and services are much higher in these cities than in the other types, suggesting that these cities have a relatively well-developed agricultural and service economy, but that these sectors do not lead to better liveability. Therefore, the relevant economic development orientations, including urban agriculture and knowledge-driven high-end services, should be targeted by them and supported by policymakers through technology, investment, and institutional guidance.

Conclusion

Chinese cities are under intense pressure to reduce carbon emissions, which is a necessary step for their further transformation and development. Existing research has demonstrated that the carbon emissions of a city are closely related to multiple urban socio-economic activities. To this end, most of the previous studies focus on the impact of carbon emissions and related policies on macro-level indicators of urban development. However, urban liveability from the citizens' perspective is also significantly affected by decarbonisation initiatives, and this is more evident in non-core cities. This study argues that different cities should implement differentiated decarbonisation trajectories to avoid the exacerbation of a decrease in liveability. In this way, this study aims to investigate the differences among Chinese non-core cities based on their various characteristics of carbon emissions, and then, the disparities across different types are explored regarding multidimensional liveability performance.

K-means clustering analysis helped to obtain four distinguishable types of China's non-core cities based on the proportion of their carbon emissions components. The detailed urban liveability exploration shows that there are also significant disparities among types. Type 1 has a small urban size and the lowest total emissions, and its liveability performance in terms of social vitality, innovation, and employment is worse than the other types. Type 2 does not have a large size, but it has good liveability performance and lower total carbon emissions. Type 3 is the category with the largest number of cities. These cities contribute to very high-carbon emissions with the largest sizes, but also bring high liveability. Finally, Type 4 is the most struggling group of cities, with the largest population, but with less favourable liveability and lower total carbon emissions. On this basis, this study further explores the relationship between carbon emissions and liveability dimensions across types using Spearman correlation analysis and Coupling analysis. This confirms that the development of Chinese non-core cities is still strongly dependent on carbon emissions. However, the degree of dependence on carbon emissions for each dimension of liveability varies across the different types, so a homogenised policy should be avoided, and instead, more targeted decarbonisation strategies should be promoted according to the characteristics of the different types.

For the first time, the typological analysis is employed to explore the disparities regarding urban liveability based on different carbon emissions, focusing on Chinese non-core cities. It expands the widely observed overall socio-economic development proxied by the productivity and profitability of different sectors into a comprehensive discussion of urban liveability, encompassing not only the economy but also housing, social vitality, innovation, greenness, public good, and dimensions closely related to citizens' daily life.

The typological study has only given a general portrait of the carbon emissions characteristics of Chinese non-core cities and their connection with liveability performance. This has limitations to some extent. The data used in this study to evaluate liveability is comprehensive and reliable, supported by a wide range of previous studies. But some dimensions could probably have richer proxies. For example, cultural vitality in this paper applies library collections as a universal indicator, but the service capacity of different cultural facilities should also be considered. Meanwhile, the public good dimension should also include indicators of governance and institutional levels to ensure the rational allocation of resources. This part of the study should be strengthened in the future as the availability of data increases. In addition, two aspects of carbon-liveability causality research are not covered in this study. On one hand, the specific causality between both needs further exploration, namely, what kind of factors influence carbon emissions, and to what extent they contribute to the performance of urban liveability. To bring certain insights to this, a further exploration on the mechanisms of carbon-liveability relationships is provided in the supplementary material. On the other hand, four types of cities are clearly defined based on the components of carbon emissions, showing variations in the performance of each dimension of urban liveability. It is still unable to know the realistic reasons behind such challenges and the applicable solution strategies. Therefore, more detailed fieldwork-based case studies need to be conducted. However, this study lays the groundwork for further exploration of the above two limitations because of its clarification of the heterogeneity among cities, its characterisation of city types, and its interpretation of the challenges of decarbonisation faced by different types.

Data availability

No datasets were generated or analysed during the current study.

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