



Extending Zipf's law: hierarchical scaling analysis and the dynamics of city-level CO₂ emissions in China

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ABSTRACT

Understanding the distributional regularities of urban CO₂ emissions is essential for advancing low-carbon urban transitions, yet remains insufficiently explored from a systemic perspective. Here, we apply Zipf's Law to examine the rank–size distribution of CO₂ emissions across 339 Chinese prefecture-level cities from 2005 to 2020. We find that urban CO₂ emissions exhibit a robust Zipf-like pattern, with approximately 78.47–80.77% of cities clustering near the theoretical equilibrium state. Over time, the Zipf index(Q) indicates a national shift from extensive toward more intensive and sustainable urban development. However, pronounced heterogeneity persists across sectors and city types. Agricultural and transportation emissions remain consistently below standard development benchmarks, whereas industrial emissions—despite approaching the ideal state in aggregate—retain sub-sectoral inefficiencies. Residential emissions show improving alignment overall, yet rural households remain markedly mismatched. In contrast, emissions from the service sector and indirect sources persistently exceed equilibrium levels, identifying them as key bottlenecks in China's low-carbon transition. Typology-specific analysis further reveals divergent pathways: industrial cities achieved early efficiency gains, service-oriented cities remain in an extensive development phase, and other city types have steadily progressed toward low-carbon optimization. By extending Zipf's Law to urban carbon emissions in a longitudinal and sector-resolved framework, this study provides new insights into the hierarchical organization, evolutionary stages, and structural constraints of urban emissions. The findings offer a quantitative diagnostic tool for differentiated and equitable carbon governance, with implications for rapidly urbanizing economies seeking to reconcile development and climate mitigation.

1. Introduction

Greenhouse gas emissions pose profound challenges to the long-term sustainability of both global climate systems and human societies (Liu et al., 2023; Shuai et al., 2017). Multiple international organizations that independently monitor global temperatures have declared 2024 to be the hottest year on record, with the global mean surface temperature exceeding 1.5°C above pre-industrial levels for the first time (Bevacqua et al., 2025; Tollefson, 2025). This milestone serves as a stark reminder

that the Earth system is entering a critical threshold, beyond which the adverse impacts of global warming may intensify substantially. Consequently, mitigating climate change through carbon emission reductions and advancing sustainable development have emerged as central priorities on the global policy agenda (Gouldson et al., 2016; Wiedmann & Allen, 2021). Cities account for approximately 60–80% of global energy consumption and are responsible for more than 70% of anthropogenic carbon dioxide (CO₂) emissions (Muneer et al., 2011; Sodiq et al., 2019). Accordingly, understanding the spatial distribution and underlying

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drivers of CO₂ emissions within urban systems is essential for advancing low-carbon transitions and promoting regional sustainable development (Zhang, M. et al., 2025).

Urbanization is a global economic and social process that has driven large-scale migration and structural transformations across industries and populations (Li & Lu, 2021). While urbanization acts as a powerful engine of economic growth and social development, it simultaneously constitutes a major source of environmental pressure. Consequently, achieving low-carbon development has become a critical pathway toward realizing sustainable development (Yang et al., 2018). Particularly in countries such as China, rapid urbanization coupled with industrial restructuring has profoundly reshaped spatial development patterns. Identifying the structural patterns of urban carbon emissions is crucial for achieving national "dual carbon" goals, including emissions peaking and carbon neutrality. However, despite extensive research on urban carbon accounting and emission determinants, the statistical regularities governing the distribution of emissions across cities remain underexplored.

Scholars generally agree that Zipf's Law provides a useful framework for exploring such distributional patterns. Originally formulated to describe word frequencies in natural languages, Zipf's Law has since been widely applied to urban systems, where it characterizes the hierarchical scaling of cities, with city population inversely proportional to its rank in the urban hierarchy. When the scaling exponent approaches unity, the system conforms to an ideal Zipf distribution, indicating a balanced urban structure between concentration and dispersion (Arshad et al., 2018). Empirical studies have repeatedly demonstrated that urban size, economic output, and other socioeconomic attributes exhibit Zipf or power-law behavior, revealing the self-organizing nature of urban systems (Appiah-Kubi & Gyambibi, 2025; Soo, 2005; Wang & Sun, 2024). Consequently, Zipf's Law has become a benchmark framework for urban empiricists seeking to understand the structure and dynamics of urban systems. In recent years, researchers have extended the application of Zipf's Law to environmental and resource-use domains (Wei et al., 2021). Research indicates that urban energy consumption, land development and construction activity, and air pollution often exhibit nonlinear scaling relationships with population size or economic scale (Muller, 2016; Wang et al., 2024; Zhang et al., 2024). These studies provide evidence that cities follow hierarchical patterns not only in terms of size and economic activity but also in their environmental metabolism. However, despite extensive research on power-law relationships at the urban scale, few studies have explicitly applied Zipf's Law to urban CO₂ emissions—that is, testing whether carbon emissions themselves conform to this law. Such an endeavor could offer new insights into the inequality, concentration, and regularity of emissions across different stages of urban development.

China is the world's largest emitter of CO₂ and one of the fastest-urbanizing economies globally (Mi et al., 2017). China's prefecture-level cities encompass a wide range of urban development stages and models. The coexistence of megacities, medium-sized and small cities, as well as industrial and service-oriented cities, forms a complex urban network with pronounced heterogeneity in emission patterns (Wiedmann & Allen, 2021). This diversity makes China an ideal case for testing whether and how urban CO₂ emissions conform to Zipf's Law, and whether such patterns persist or evolve over time. Examining this regularity across multiple time periods can reveal whether emissions become increasingly concentrated or more dispersed alongside economic and structural transformations.

In summary, previous studies have generally assumed that urban population and economic scale conform to Zipf's Law (Arshad et al., 2018), with only limited extension to environmental variables (Wei et al., 2021). Meanwhile, most research on urban carbon emissions has focused on aggregate scale comparisons, carbon-intensity indicators, or econometric testing of the Environmental Kuznets Curve (EKC) (Shen et al., 2024). Such approaches rarely examine the hierarchical structural configuration of emissions within national urban systems, nor do they

systematically investigate how scaling dynamics vary across sectors and city typologies over time. To address these gaps, we apply Zipf's Law to investigate the spatiotemporal characteristics of CO₂ emissions across 339 Chinese cities. Using a unified dataset spanning 2005, 2010, 2015, and 2020, we examine whether the rank–size distribution of city-level CO₂ emissions exhibits a Zipf-like pattern and how this pattern has evolved over the past 15 years. Importantly, the analysis extends beyond total emissions to encompass multiple economic and functional sectors, including agriculture, industry, services, transportation, and households. This multidimensional approach enables a more nuanced assessment of whether Zipf's Law holds consistently across emission sources with distinct socioeconomic characteristics. These empirical tests enrich the methodological toolkit of urban carbon research and provide policy-relevant insights for cities in China and other developing countries that have not yet reached peak carbon emissions. In turn, these findings inform differentiated and equitable carbon governance strategies across cities at different stages of development.

2. Materials and methods

2.1. Theoretical framework

Zipf's Law is an empirical regularity describing word frequency distributions in natural language, whereby the frequency of a word is inversely proportional to its rank (Wang et al., 2017). As research fields have expanded and converged, a wide range of phenomena have been shown to follow this law (Ausloos et al., 2016; Chen, 2012). In parallel, Zipf's Law has been extensively validated and applied in urban studies (Arshad et al., 2018; Batty, 2008; Wang et al., 2024). Urban development is inherently complex, involving multiple interacting factors and distinct developmental stages. Consequently, Zipf's Law cannot be universally applied across all urban development contexts. Across the urban development trajectory, cities that have reached relatively advanced stages often conform to this distributional law, as observed in many developed countries in Europe and North America (Arshad et al., 2018; Hackmann & Klarl, 2020). By contrast, cities in some developing countries remain in early stages of economic development and often deviate from the ideal state implied by Zipf's Law (Arshad et al., 2019). China has experienced rapid development in recent decades, with many cities effectively compressing or bypassing early and acceleration stages of growth. Therefore, applying Zipf's Law to assess the degree of balance in China's urban development represents a theoretically grounded and empirically meaningful endeavor (Akhundjanov et al., 2017).

Urban economic development relies on the support of multiple industrial sectors, which simultaneously generate substantial CO₂ emissions. Extensive empirical research has identified a U-shaped relationship between CO₂ emissions and levels of economic development (Chen et al., 2020; He et al., 2024; Liu, J.X. et al., 2019). Once economic development reaches a certain threshold, cities tend to undergo industrial restructuring and technological upgrading, leading to constraints on carbon emissions. Accordingly, CO₂ emissions can serve as an indicator of the balance and quality of urban development. Notably, under the influence of environmental awareness, regulatory policies, and technological progress, some cities systematically adopt and diffuse advanced clean technologies during the transition from early development stages to accelerated growth stages. Such generational upgrades in "development models" can lower overall emission peaks and may even enable cities to reach peak emissions earlier than conventionally projected (yellow line) (Ridzuan et al., 2020). As cities transition from accelerated growth stages to advanced phases characterized by efficiency, intensification, and sustainability, overall societal emissions are substantially reduced (green line). Moreover, at high levels of economic development, environmental quality may partially recover or improve. This evolutionary pattern can be characterized by the coefficient α in the revised Zipf's Law. When most cities remain in early stages of economic development, the overall development scale falls short of

the ideal conditions implied by Zipf's Law, with α significantly less than 1. As a large number of cities enter accelerated development stages, overall urban development begins to conform to this distributional law, at which point α approaches 1. This implies that carbon emissions are largely commensurate with urban development, with development scales in most cities matching their underlying structural complexity. Similarly, as the number of cities entering terminal development stages increases, the value of α exceeds 1, indicating that urban development, or the evolution of industrial sectors, is undergoing a transition toward sustainability. This study draws an analytical analogy between the Zipf scaling coefficient and the developmental phases described by the Environmental Kuznets Curve (EKC). This mapping is conceptual rather than mechanistic. While the EKC describes the dynamic relationship between economic growth and environmental degradation over time, the Zipf coefficient reflects the cross-sectional structural configuration of emissions across cities at a given time. By interpreting Q as a structural indicator of concentration or dispersion, this paper links distributional patterns to plausible developmental stages, without implying that Zipf conformity itself constitutes environmental optimality. Given that Zipf's Law has rarely been examined from a time-series perspective—particularly in the context of CO₂ emissions—this study's validation of the law in China from 2005 to 2020 represents a novel and methodologically meaningful contribution (Fig. 1).

2.2. Data sources and classification

All CO₂ emission data used in this study are derived from the China High-Resolution Emission Grid Database (CHRED). CHRED is constructed using a bottom-up approach based on enterprise-level, sector-level, and city-level data. Enterprise-level data are obtained from China's National Pollutant Discharge Survey and routine pollution reporting systems, covering more than 1.5 million enterprises. Sectoral- and city-level data are obtained from official statistical yearbooks, policy documents, reports, surveys, and expert consultations (Cai et al., 2019). This dataset encompasses nearly all cities in China, is updated at five-year intervals, and exhibits high accuracy and strong temporal continuity.

The study area comprises 339 cities (prefecture-level administrative units) in China, covering emission sectors including agriculture, transportation, industrial energy use, industrial processes, urban residential, rural residential, services, and indirect emissions. Given the substantial heterogeneity in development patterns among Chinese cities, we further categorized cities based on their sectoral structure. Cities in which the secondary industry accounts for $\geq 50\%$ of urban GDP are classified as industrial cities; those in which the tertiary industry accounts for $\geq 50\%$

are classified as service-oriented cities; cities not meeting either criterion are classified as other city types (Wei et al., 2021).

2.3. Methodology

Zipf's Law was originally proposed by George Kingsley Zipf through extensive statistical analyses of word frequencies in English texts, building upon and testing earlier quantitative formulations (Wang et al., 2005). The law describes a quantitative relationship between the frequency (F) of a word in a corpus and its corresponding rank (r). Accordingly, the law can be formally expressed as follows:

$$F(r) * r = C$$

In the equation, $F(r)$ denotes frequency, r denotes rank (i.e., the position in the frequency distribution), and C is a proportionality constant. As Zipf's Law has been applied across fields such as linguistics and economic geography, numerous scholars have proposed revised formulations of this relationship (Wu et al., 2020).

$$F(r)^\alpha * r = C$$

In this study, the relationship between urban carbon emissions and city rankings is characterized using a revised form of Zipf's Law. In this formulation, $F(r)$ no longer represents word frequency but instead denotes a city's CO₂ emissions, while the variable r represents a city's national ranking in terms of CO₂ emissions, ordered from highest to lowest. The parameter α represents the scaling exponent, indicating the degree of concentration or dispersion in emissions across cities. Under this formulation, urban CO₂ emissions are inversely proportional to city rank. A natural logarithmic transformation is typically applied to linearize the relationship and facilitate empirical estimation. The resulting log-linear form is expressed as follows:

$$\text{Log}F(r) = -1/\alpha * \text{Log}(r) + 1/\alpha * \text{Log}(C)$$

For analytical convenience, we define $Q = 1/\alpha$. The resulting formulation can then be empirically tested using ordinary least squares (OLS). The estimation results can yield one of the following four scenarios. (1) $0 < \alpha < 1$ ($Q > 1$) indicates that the ideal state implied by Zipf's Law has not yet been achieved. Urban development remains at an early stage, and either overall city growth or sectoral development is still characterized by extensive expansion. (2) $\alpha = 1$ ($Q = 1$) represents the ideal distribution of urban carbon emissions implied by the law. These cities generally exhibit a stable and balanced development trend. This state is theoretically defined; in practice, the more common condition is $\alpha \approx 1$ ($Q \approx 1$). (3) $\alpha > 1$ ($0 < Q < 1$) suggests that carbon emissions

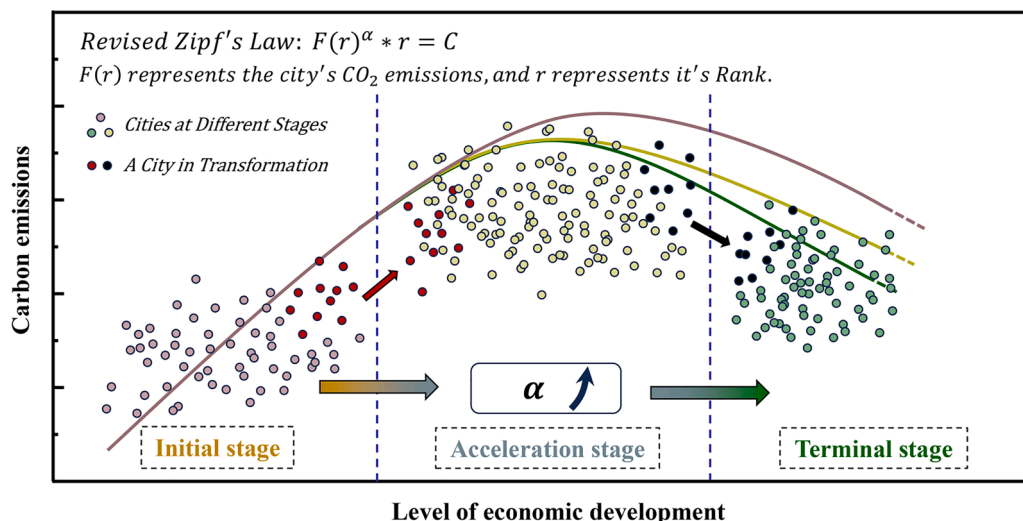


Fig. 1. The theoretical framework of the study.

from cities or industrial sectors are undergoing sustained optimization, with urban and industrial development transitioning toward a stage of advanced agglomeration and sustainable development. (4) $\alpha \leq 0$ ($Q \leq 0$) lacks practical interpretability in empirical urban systems. To validate the robustness of the Zipf-like scaling relationship, this study compared the log-log OLS model with alternative distributional specifications, including lognormal and maximum-likelihood-estimated power-law models. Model performance was evaluated using AIC and BIC criteria. Results consistently indicate that the log-log OLS model provides a competitive (or superior) fit relative to alternative distributions, supporting the stability of the reported scaling relationships (Supplementary Table 1). It is important to clarify that conformity to Zipf's Law reflects a structural property of the emission distribution rather than a direct measure of environmental performance. A value of $Q \approx 1$ indicates that the rank-size distribution of emissions approximates the theoretical Zipf equilibrium, meaning that emission scales are proportionally distributed across the urban hierarchy. This structural proportionality should not be interpreted as evidence of absolute sustainability or optimal environmental performance. Instead, it reflects a balanced configuration in which the relative scale of emissions is commensurate with the relative scale of urban development. When Q departs from 1, the emission distribution becomes either more concentrated or more dispersed than expected under the theoretical equilibrium, signaling a structural mismatch between emissions allocation and the urban hierarchy rather than directly indicating whether a city or sector performs well or poorly in environmental terms. In this study, we interpret deviations from $Q = 1$ as signals of different structural-developmental stages, which may correspond to distinct environmental governance challenges, rather than as normative judgments of sustainability.

Zipf's Law is also referred to as the Law of Least Effort. Theoretically, $Q = 1$ corresponds to a state of least effort; however, this ideal condition is rarely attained in practice. In empirical applications, cities located at "Intermediate Frequency" along the fitted distribution are more likely to approximate this state, whereas cities at "Low Frequency" and "High Frequency" correspond, respectively, to early development stages and more advanced, optimized stages of development. Their classification was accomplished by filtering city sample data and determining the

classification based on the slope relationship between the sample data and the fitted curve of Zipf's law.

3. Results and analysis

3.1. Total-scale temporal response

This study applies a revised form of Zipf's Law to examine the relationship between CO₂ emissions and city rankings across 339 Chinese cities from 2005 to 2020 (Fig. 2). From the perspective of total emissions, the majority of cities (78.47%–80.77%) exhibit a rank-size distribution that closely approximates the theoretical Zipf scaling relationship, and the law provides a strong statistical characterization of this relationship, with R² values consistently exceeding 0.6. The Zipf scaling coefficient (Q) captures the degree of concentration or dispersion of emissions across cities at a given time, reflecting the cross-sectional structural relationship between emission scale and urban rank rather than absolute environmental performance. Over the study period, this structural relationship has evolved, as evidenced by systematic changes in Q . In 2005, urban CO₂ emissions slightly exceeded the level implied by urban development ($Q=1.09$), whereas by 2020, Q had declined steadily to below unity ($Q=0.91$), indicating a sustained reduction in the carbon intensity associated with urban development.

Further insights emerge when cities are categorized by rank. "Intermediate Frequency" cities, which account for nearly 70% of all Chinese cities, exhibit carbon emissions broadly consistent with their development levels and approximate the most efficient state under Zipf's Law, reflecting their position in an accelerated growth phase. "High Frequency" cities constitute a relatively small share (approximately 10%) and generally display lower carbon emissions than those implied by standard urban development levels. These cities are typically economically advanced and densely populated, including Beijing, Tianjin, and Shanghai. However, transitioning from accelerated growth to intensive and sustainable development remains a substantial challenge, with only seven cities successfully completing this transition over the past fifteen years. In contrast, "Low Frequency" correspond to those in early development stages, with representative regions including Xinjiang and Tibet, where cities are shaped by interior locations, high-altitude plateaus, arid

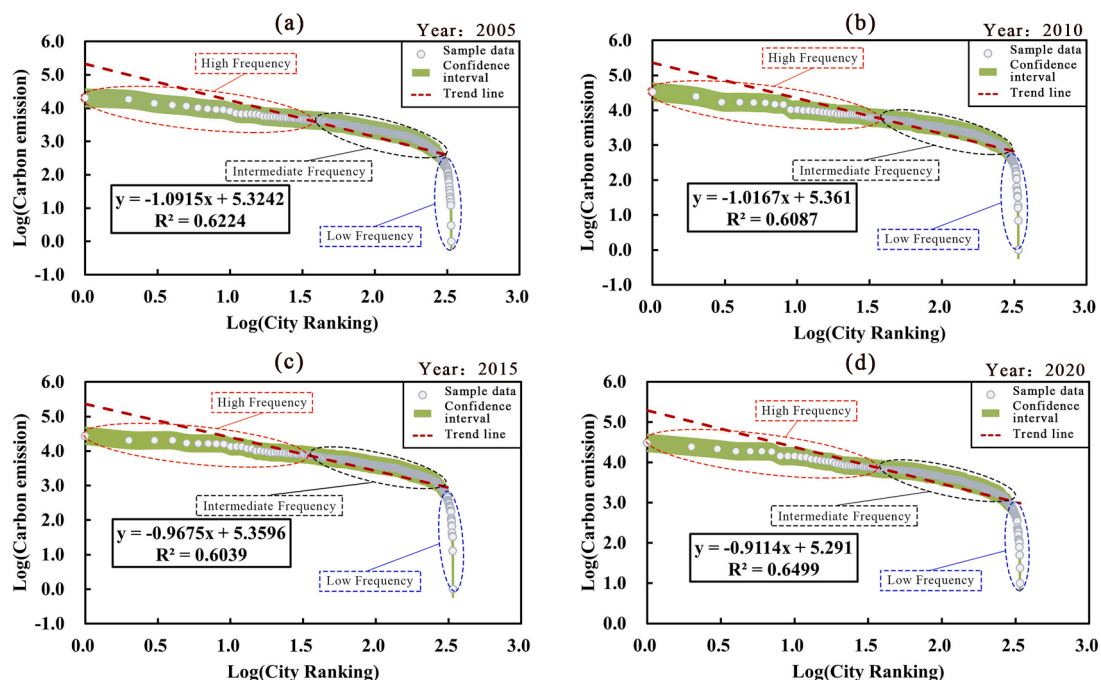


Fig. 2. Response of the temporal Zipf fit for the total scale.

environments, and distinct cultural contexts, resulting in relatively slow economic growth and low levels of urbanization. It should be emphasized that conformity to Zipf's Law does not imply environmental optimality; rather, Q serves as a structural indicator that can be analytically linked to plausible developmental stages analogous to those described by the Environmental Kuznets Curve, without implying a direct normative relationship with environmental outcomes.

3.2. Micro-level temporal responses

3.2.1. Sectors in a state of extensive development

The Zipf index Q for the agricultural sector declined steadily from 0.91 to 0.85 over the study period and remained consistently below unity (Fig. 3 a-b and S1). This pattern indicates that agricultural carbon emissions have persistently remained below the levels implied by standard development trajectories, reflecting an intensively efficient development mode. The coefficient of determination (R^2) fluctuated narrowly around 0.70, indicating that the rank-size distribution of agricultural carbon emissions closely conforms to Zipf's Law and exhibits strong regularity. From a distributional perspective, the share of "Intermediate Frequency" cities increased from 63.13% in 2005 to 67.26% in 2020, while the proportions of "Low Frequency" and "High Frequency" cities both declined, indicating an overall improvement in matching efficiency.

In contrast, the Q value for the transportation sector gradually approached unity, increasing from 0.89 in 2005 to 0.93 in 2020 (Fig. 3 c-d and S2). Over the same period, the coefficient of determination (R^2) rose from 0.68 to 0.74, indicating enhanced regularity in the rank-size distribution. These results suggest that transportation-related carbon emissions have also remained below the levels implied by standard urban development over the long term. Against the backdrop of recent policies promoting public transportation in China, the transportation sector appears to have re-entered a phase of accelerated growth, potentially reshaping its future emissions trajectory. (Qi et al., 2025).

3.2.2. Sectors approaching a state of balanced development

The overall Q value for the industrial sector exhibited the most pronounced decline over the study period, decreasing from 1.64 to 1.03

(Fig. 4 a-b and S3). This trend indicates that the industrial sector as a whole is transitioning from a state of substantial deviation from the ideal toward a condition closer to the standard state. Within this category, the industrial energy sector—the dominant contributor to carbon emissions, with a long-term contribution rate exceeding 70%—experienced a steady decline in its Q value from 1.28 in 2005 to 1.14 in 2020 (S4). Despite this improvement, the Q value remained consistently above unity, indicating that carbon emissions in this sector continue to exceed ideal levels and reflect an overall pattern of extensive development. From a distributional perspective, the share of "Intermediate Frequency" cities fluctuated within a narrow range of 65%–71%, reaching 66.67% in 2020 after peaking at 70.80% in 2015. Over the same period, the proportion of "High Frequency" cities increased from 9.73% to 11.80%, while the share of "Low Frequency" cities rose from 19.47% to 21.53%. These shifts indicate that, despite many cities maintaining relative equilibrium, both "High Frequency" cities facing intensified emission pressures and "Low Frequency" cities with underdeveloped have increased in number. A similar pattern is observed in the industrial process sector (S5), suggesting that intra-sectoral disparities may be widening and that the overall optimization process is encountering bottlenecks and progressing slowly. The industrial sector therefore remains the central focus of future carbon emission reduction efforts.

Carbon emissions in the household sector exhibit pronounced imbalances. The overall Q value for the household sector, encompassing both urban and rural areas, declined from 1.15 to 0.94 over the study period, with a goodness-of-fit (R^2) exceeding 0.72 (Fig. 4 b-c and S6). By 2020, the estimated value approached unity ($Q \approx 1$), indicating that the relationship between residential carbon emissions and urban development has shifted from an extensive mode toward the theoretical ideal state. From a more granular perspective, the Q value for urban household lifestyles declined from 1.12 in 2005 to 1.05 in 2020, moving closer to equilibrium (S7). Within the rank distribution, the share of "Intermediate Frequency" cities increased from 68.44%, maintaining a relatively stable structural composition. In contrast, the Q value for rural households remained persistently higher (1.12 in 2020), with approximately 24.19% of cities classified as "Low Frequency"—the highest proportion among all sectors (S8). Although the share of "Intermediate Frequency" cities increased from 57.52% to 64.60%, more than one

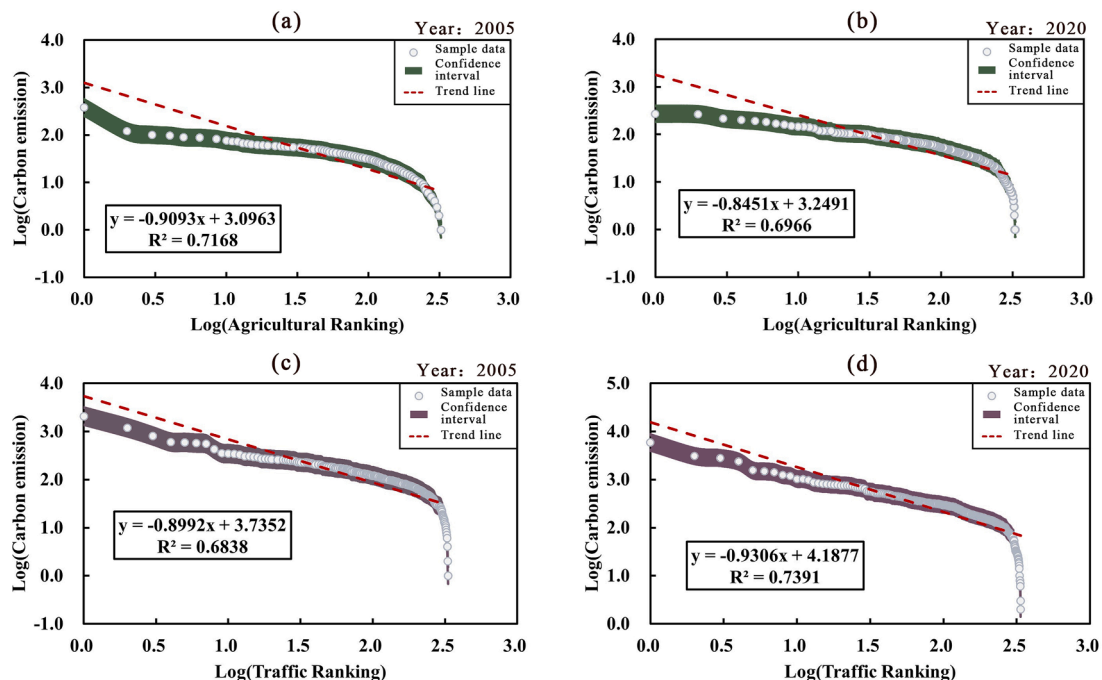


Fig. 3. Zipf's law fitting in the agriculture and transportation sectors.

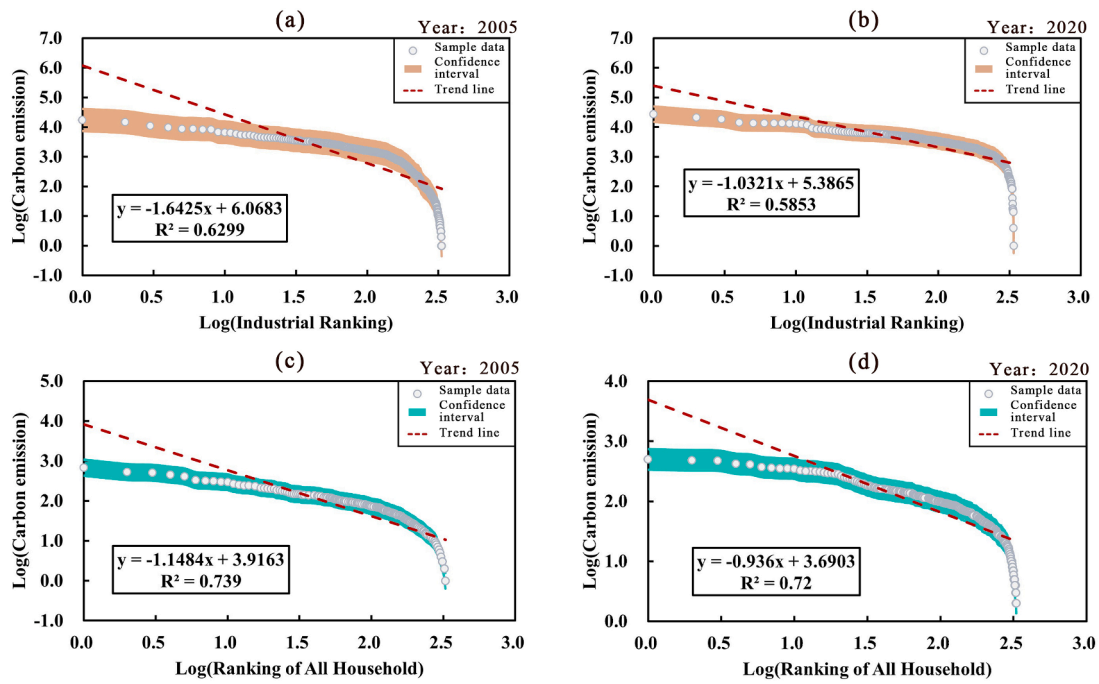


Fig. 4. Zipf's law fitting in the industry and household sectors.

third of rural areas still exhibit pronounced mismatch. This outcome reflects substantial regional disparities and considerable optimization potential in energy consumption and emission patterns in rural living.

3.2.3. Sectors in a state of optimized development

The Q index for the service sector increased steadily from 1.14 in 2005 to 1.25 in 2020 (Fig. 5 a-b and S9). Notably, the Q value exceeded unity in all four observation years and remained relatively high in absolute terms, indicating that carbon emissions in the service sector substantially exceeded the levels implied by standard urban development. This suggests that the development mode of the service sector has yet to

move beyond a relatively carbon-intensive stage. The expansion of the service sector continues to be associated with high carbon costs, underscoring the urgency of its transition toward greener and lower-carbon pathways. The coefficient of determination (R^2) for the service sector is the highest among all sectors, reaching 0.78 in 2020 and as high as 0.88 in 2005. This indicates that the rank distribution of service-sector carbon emissions is strongly aligned with the urban size hierarchy and closely conforms to Zipf's Law, likely reflecting the close linkage between service-sector development, urban scale, and overall economic output. "Intermediate Frequency" cities dominate the service sector, accounting for 66.67%–70.21% of all cities. After peaking at over 70%

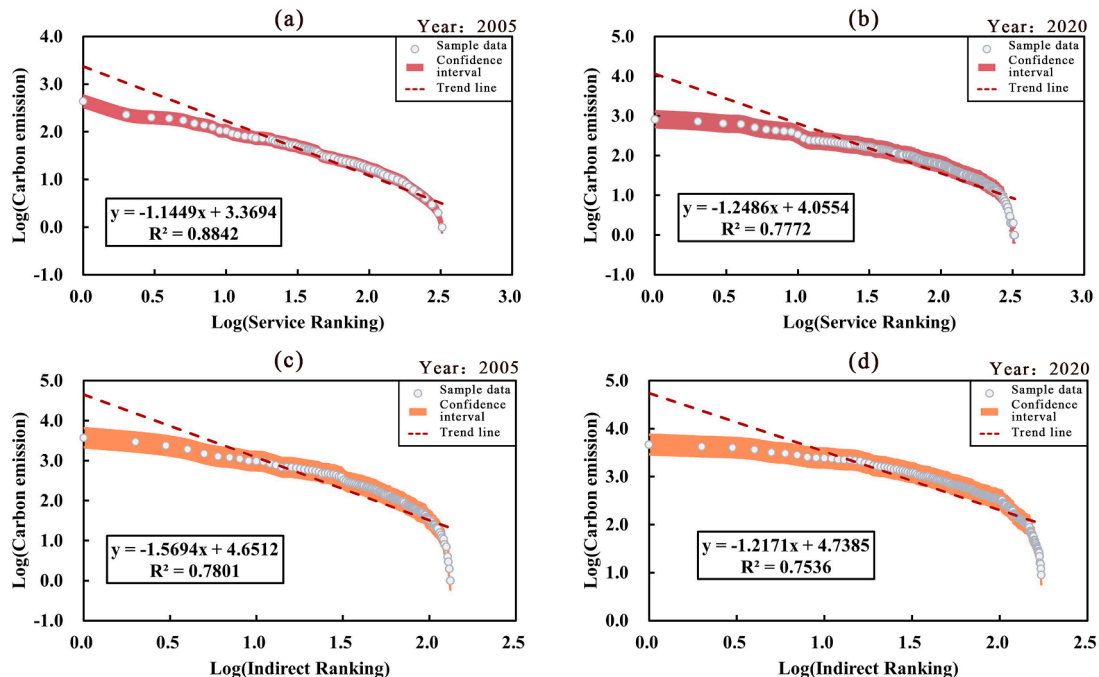


Fig. 5. Zipf's law fitting in the service sector and indirect emissions.

between 2010 and 2015, this share declined to 66.67% by 2020, while the proportion of "High Frequency" cities increased from 9.73% to 11.80%. These shifts suggest that, under the strong coupling between service-sector development and city scale, some cities have moved toward more optimized emission–development states. For example, Chongqing and Chengdu transitioned from medium-rank to high-rank categories as they developed, whereas Puer City shifted from low-rank to medium-rank.

Indirect carbon emissions conform to Zipf's Law, with a goodness-of-fit (R^2) exceeding 0.70 throughout the study period (Fig. 5 c-d and S10). However, the Q value for this sector remained above unity in all observation years. Although Q declined from 1.57 to 1.22 over time, it consistently represented the highest value among all sectors. These results indicate that carbon emissions from the indirect sector persistently exceed the levels implied by urban development. The sector therefore remains in an early stage of extensive development and constitutes a key domain requiring sustained optimization.

3.3. Temporal responses across different city categories

Carbon emission characteristics vary markedly across different city types. Industrial cities have transitioned from a high-efficiency, low-

carbon state toward a more balanced development pattern, while service-oriented cities largely remain in an early stage characterized by relatively high carbon emissions. Other city types have shifted from a balanced state toward a phase of higher efficiency and more intensive development. Meanwhile, the distribution of cities across these categories has evolved over time: the number of service-oriented cities has increased, whereas industrial and other city types have declined, with this shift being particularly pronounced during the 2015–2020 period (Fig. 6 a).

Throughout the study period, service-oriented cities exhibited a pronounced mismatch between carbon emissions and development levels (Fig. 6 b-e). Particularly during the 2005–2015 period, the Q value was substantially greater than unity, indicating a failure to attain the ideal state implied by Zipf's Law. At that time, the share of cities oriented toward service-driven development remained relatively low, accounting for only 6.85%–17.26% of the total. These service-oriented cities were at a nascent stage of development, with their development models and structural configurations still exploratory. Most were located in China's eastern coastal regions or along the Yangtze River, including Shanghai, Shenzhen, Wuhan, and Tianjin, and were characterized by highly concentrated economic activity and strong economic and technological foundations. By 2020, the Q value had gradually approached unity,

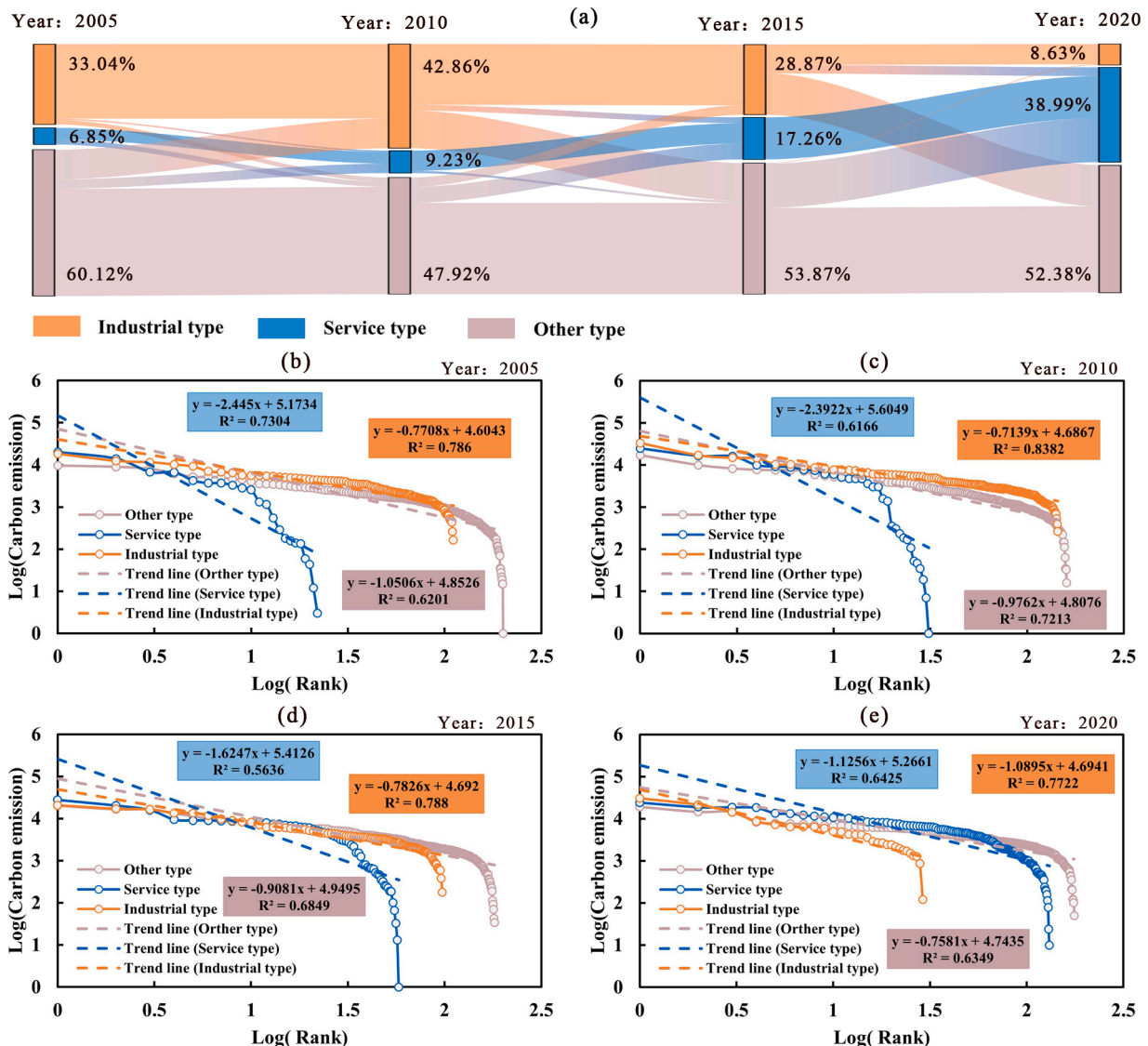


Fig. 6. Zipf's law fitting of different types of cities based on industrial structure.

while the share of service-oriented cities increased to 38.99%. Nevertheless, as many cities have only recently transitioned to service-oriented models, service-oriented cities as a whole remain at a relatively early stage and require further optimization to support sustainable development.

The development trajectory of industrial cities is markedly more low-carbon, with their CO₂ emissions exhibiting a rank-size distribution that closely follows Zipf's Law ($R^2 > 0.7$). During the 2005–2015 period, industrial cities underwent a process of continuous optimization and made substantial contributions to China's economic growth. Industrial cities account for 28.87% to 42.86% of all cities nationwide. These cities effectively leveraged their resource endowments to promote efficient and spatially concentrated industrial development, with representative examples found in resource-rich provinces such as Inner Mongolia and Shanxi. Notably, by 2020, the number of industrial cities declined sharply, with only 8.63% of cities still maintaining an industry-dominated development model. At the same time, industrial cities gradually approached a state of balanced development, with the Zipf index converging toward unity ($Q = 1.09 \approx 1$). During the 2005–2015 period, the development of other city types was largely aligned with their carbon emissions (Q approaching unity), indicating generally balanced urban development. These cities include major energy-producing cities such as Chongqing, transitioning resource-based cities, and large cities with agriculture-dominated economic structures. By 2020, the development trajectories of these cities had shifted toward more efficient and intensive models, accompanied by increasingly low-carbon and sustainable outcomes.

4. Discussion

4.1. Implications from typology- and sector-specific research

Cities are complex socio-economic-ecological systems, whose development is reflected not only in spatial form and economic characteristics but also in the relationship between resource consumption and environmental responses (Zhang, Y.G. et al., 2025). Prior research indicates that urban land use and industrial development exert a profound influence on carbon emissions (Jing et al., 2022; Zhou et al., 2021). For example, orderly and intensive land use can mitigate emissions through optimized spatial structures and management practices (Wu et al., 2015), while efficient and accessible transportation systems also shape a city's carbon footprint (Lv et al., 2022). Accordingly, this study analyzes cities through the lens of environmental responses to urban development, aiming to elucidate disparities in carbon emission contributions.

The ideal state of urban development and carbon emissions corresponds to a one-to-one ratio between economic output and carbon emissions, representing the most optimal manifestation of Zipf's Law. However, this "least-effort" development model is unsustainable in practice and does not satisfy contemporary demands for urban growth. In response, China has enacted a series of policies and implemented multiple measures aimed at mitigating emissions (Wang et al., 2023). At the national level, the response coefficient Q for Chinese city carbon emissions and rankings reflects these mitigation efforts, declining from 1.09 to 0.91. Overall, these trends suggest a gradual redistribution of emission burdens across cities, which may be consistent with broader efforts toward decoupling.

Nevertheless, this does not imply that China can afford complacency. Carbon emissions vary markedly across industrial sectors, which continue to require optimization and the pursuit of low-carbon transformation. In the residential sector, urban carbon emissions largely conform to Zipf's Law, and temporal variations in the Q index closely align with changes in total national emissions. The industrial sector has been the primary driver of China's economic growth, supported by substantial capital and technological investments, and has transitioned from an initial phase to an accelerated development stage (Jia et al.,

2020). Benefiting from economies of scale, technological upgrading, and spatial concentration within established industrial clusters, emissions became increasingly organized around a stable hierarchical structure. This consolidation reduced extreme deviations in the rank-size distribution, allowing the industrial sector to approach the Zipf equilibrium ($Q = 1.03 \approx 1$) in 2020. Although the Q value for indirect emissions declined, this sector remains in an early developmental stage, reflecting the reliance of major cities, such as Shanghai and Shenzhen, on energy supplied from other regions (Liu, X.Y. et al., 2019).

China is an agricultural powerhouse with a rich agricultural culture and history (Zhou et al., 2024). The agricultural sector entered an phase of large-scale, low-carbon development early on, supported by China's rich agricultural heritage. The transportation sector is strongly influenced by national infrastructure policies and major logistics hubs (Jin et al., 2012). From 2010 to 2015, China initiated comprehensive systemic reforms in transportation (Qi et al., 2025), which contributed to the significant fluctuations observed in Q during 2015. The service sector remains in an early developmental phase, characterized by $Q > 1$, indicating a relatively dispersed emission structure. This pattern likely reflects the uneven expansion of modern services across cities during China's structural transformation, where large metropolitan areas concentrate high-end services while smaller cities rely on lower-productivity, energy-intensive service activities. Such spatial asymmetry contributes to rank-size deviations from equilibrium. From 2005 to 2020, China underwent an integrated process of industrial expansion, industrial relocation, and low-carbon development, with numerous urban development models transitioning from industry-dominated to service-dominated approaches (Cui et al., 2024; He et al., 2016; Wang & Lin, 2023). Research perspectives across different city types also underscore that China still faces significant challenges in achieving comprehensive low-carbon development. Carbon emissions in service-oriented cities remain elevated relative to standard benchmarks, yet the transition from industrial to service-oriented urban models continues to define China's predominant trajectory. (Ma et al., 2023). Sector-specific analysis underscores that the industrial sector remains the primary contributor to national emissions. Although industrial cities and the industrial sector exhibit Zipf coefficients close to unity, further efforts are required to decouple carbon emissions from economic growth and to advance urban low-carbon development more effectively.

Although the Zipf coefficient (Q) primarily captures the structural distribution of emissions within the urban hierarchy, it can also function as a diagnostic instrument for differentiated carbon governance. Put simply, when Q departs from 1, the urban emission system no longer conforms to the proportional rank-size structure implied by Zipf's law: some parts of the urban hierarchy bear disproportionately high emission burdens, whereas others contribute less than expected. Such deviations help identify where structural adjustment, rather than uniform reduction pressure, may be most needed. While Q does not directly measure environmental performance, it reveals whether emission burdens are spatially concentrated or dispersed, thereby informing policy prioritization. When $Q > 1$, emissions are disproportionately concentrated in higher-ranked cities. In such cases, mitigation strategies may prioritize large metropolitan areas, where marginal reductions could generate substantial aggregate impacts. Policymakers may therefore consider stricter carbon-intensity targets, accelerated peak-emission timelines for core cities, and structural upgrading of dominant industries. When $Q = 1$, the structural balance of emissions suggests that reduction responsibilities may be proportionally allocated across cities. When $Q < 1$, emissions are relatively dispersed among medium-sized or lower-ranked cities, implying that coordinated regional policies are needed to prevent carbon leakage and horizontal diffusion. Similar logic applies at the sectoral level: industries with $Q > 1$ indicate concentrated emission centers suitable for targeted technological upgrading and regulatory tightening, whereas $Q < 1$ reflects spatially diffuse sources requiring integrated regional governance rather than isolated interventions.

Temporal changes in Q further illuminate the evolution of spatial carbon structures. A declining Q signals increasing dispersion and the need for strengthened interregional coordination, whereas a rising Q indicates growing concentration in major cities, potentially warranting centralized regulatory responses. From an urban planning perspective, these hierarchical scaling patterns suggest that emission reduction strategies should vary according to city size and functional position within the urban system. For large metropolitan areas and high-ranking cities, especially in sectors with $Q > 1$, priorities should include stricter carbon-intensity control, service-sector decarbonization, clean energy substitution, and the upgrading of dominant industries and buildings. For medium-sized cities, where emissions are more closely aligned with the urban hierarchy, the focus should be on preventing lock-in to carbon-intensive growth through compact land use, efficient transport systems, and early technological upgrading. For lower-ranked or more spatially dispersed cities, particularly where $Q < 1$ indicates a broader diffusion of emission burdens, stronger regional coordination mechanisms are needed to avoid carbon leakage and uneven mitigation capacity. Importantly, the Zipf index should be regarded as an early-warning indicator of macro-structural shifts rather than a direct measure of sustainability. By complementing traditional intensity-based metrics, Zipf-based diagnostics enable policymakers to avoid uniform reduction strategies and instead adopt spatially and sectorally differentiated approaches aligned with urban hierarchies.

4.2. Insights from micro-level exploration for urban management

The application of Zipf's Law provides insights into urban management from a more granular perspective. Transitions between stages of urban development are exceptionally challenging, as they are shaped by multiple interacting factors, including industrial structure, resource endowments, and technological capacity (Wang et al., 2019a). This study identifies four distinct urban development states or pathways at the critical transition point between development stages, a dimension that has received limited attention in prior research.

Type I represents the critical transition zone between the initial development phase and the acceleration phase, within which four distinct urban development trajectories can be identified (Fig. 7). The first trajectory (Type I ①) involves cities that achieve a developmental leap during the study period and successfully sustain this momentum, thereby entering the ideal range described by Zipf's Law. This pathway is observed in cities across China's Yunnan, Guangxi, and Guizhou provinces. Cities following this trajectory must accurately assess their carbon emission characteristics and, while stabilizing industrial development,

proactively pursue industrial restructuring and reductions in energy consumption intensity. The second trajectory (Type I ②) consists of cities that have regressed to an earlier stage of development, while the third (Type I ③) comprises cities that failed to successfully complete the transition between development stages. After entering an accelerated development phase, some cities experience industrial and population decline due to the deterioration of dominant industries and the failure of emerging industries to replace them. Overreliance on resource extraction and the inability to shift from investment-driven construction to operation- and service-oriented development contribute to declining urban vitality. (Zhang, Y.G. et al., 2025). For such cities, priority should be given to stabilizing developmental transitions rather than emphasizing immediate emissions reduction. The fourth trajectory (Type I ④) comprises cities that remain in a state of impending transition and have not yet crossed the developmental threshold. Although these cities may exhibit emerging growth engines, their economic development continues to rely on traditional drivers such as land expansion and resource extraction. For these cities, industrial systems should prioritize incremental improvements through the adoption of existing green technologies, without necessitating major structural transformation. Urban development should gradually shift from production-oriented cities toward comprehensive, multifunctional urban systems.

Similar to Type I, Type II cities also exhibit four distinct developmental trajectories. The first trajectory (Type II ①) consists of cities that have achieved a difficult yet necessary developmental upgrade. In these cities, the core challenge shifts from emission reduction to systemic environmental governance and the cultivation of sustainable resilience. Sustainable development at this stage requires transformations in production, consumption, and behavioral patterns, supported by mature environmental governance systems rather than intensified administrative intervention (Ahmad, 2025a, b). Emission reduction measures and policies should therefore be designed by local governments in accordance with city-specific developmental characteristics (Wang et al., 2019a; 2019b). The second (Type II ②) and third (Type II ③) trajectories reflect processes of environmental regression or rebound. Such setbacks often stem from coordination failures rather than the absence of policy instruments. At this stage, the marginal benefits of environmental technologies and policy measures diminish, and environmental progress increasingly depends on the continuous renewal of development structures and technologies. Urban management should therefore place greater emphasis on continuous structural upgrading, institutional vigilance, and systemic resilience. The fourth trajectory (Type II ④) indicates that a city has accumulated sufficient scale, yet achieving further advancement requires a qualitative breakthrough. City

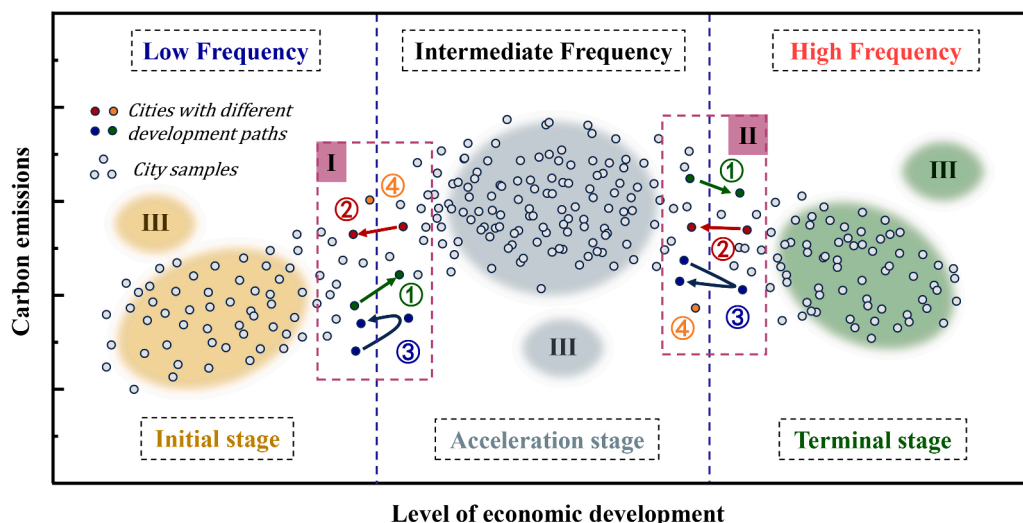


Fig. 7. Schematic diagram of urban development status or pathways.

administrators must recognize that such a leap cannot be achieved by replicating previously effective approaches, but instead requires abandoning strategies that have lost their effectiveness.

Type III comprises cities that remained stable within a particular development stage throughout the study period. This pattern has been widely identified in the literature, with numerous studies proposing corresponding pathways for clean and sustainable development. Cities at an early stage of development face the most urgent need to transform their prevailing development philosophies and growth models (Wei et al., 2021). Cities in the mid-acceleration stage must confront the intensive consumption and depletion of non-renewable, high-pollution energy sources, while proactively initiating industrial restructuring and technological upgrading (Wang, Y.N. et al., 2019; Yao et al., 2018). Cities in the intensive development stage are typically mature large cities, for which policy priorities should focus on accelerating the deployment of clean energy (Ahmad, 2025b) and fostering the growth of high-end production and service sectors (Sarkodie et al., 2020).

4.3. Contributions from academic and theoretical perspectives

Beyond its empirical findings, this study advances academic understanding in several important respects. First, it extends the temporal validation and theoretical application of Zipf's Law within urban research. Although Zipf's Law has been widely used to describe hierarchical distributions of urban population and economic output, its application to environmental dimensions—particularly carbon dioxide emissions—remains limited. By examining 15 years of multi-sectoral emissions data across Chinese cities, this study confirms the robustness of Zipf-like scaling across sectors and time. In doing so, it broadens the theoretical scope of hierarchical scale analysis from socioeconomic systems to the domain of urban environmental metabolism. Second, this study refines the interpretation of the Zipf coefficient. Conventional scale indices are typically treated as statistical descriptors of concentration or dispersion (Liang et al., 2024). Here, the Zipf index (Q) is conceptualized as a structural indicator of hierarchical emission allocation within urban systems. Importantly, Q is positioned strictly as a diagnostic metric of spatial emission organization rather than a direct measure of environmental performance. This clarification establishes conceptual boundaries between statistical regularity and sustainability outcomes, thereby preventing overly normative interpretations of Zipf consistency. Third, the study enriches theoretical perspectives on the EKC by integrating hierarchical scaling analysis into developmental interpretation. Rather than implying a deterministic causal relationship, the mapping of Q to developmental stages introduces a complementary structural dimension to the dynamic EKC framework. This integration provides a novel lens through which to interpret how emission hierarchies evolve alongside broader economic transitions. Fourth, the typology- and pathway-based analysis advances urban transition theory. Whereas much existing literature implicitly assumes linear development trajectories (Wang et al., 2021), this study reveals heterogeneous, multi-path, and potentially reversible transition processes across urban types and sectors. Urban low-carbon transitions may stall or regress under structural, technological, or policy constraints. Recognizing such nonlinearity contributes to a more realistic and nuanced understanding of urban transformation under rapid industrial restructuring and intensifying climate governance. Collectively, these contributions deepen theoretical insights into urban environmental systems while positioning Zipf's Law as a complementary analytical tool within urban science, environmental economics, and sustainable development research.

4.4. Limitations and uncertainties

This study examines whether the rank-size distribution of city-level CO₂ emissions conforms to a Zipf-like pattern and how this relationship has evolved over the past 15 years. However, the analysis is based on

four benchmark years (2005, 2010, 2015, and 2020) rather than annual observations, which limits the ability to capture finer temporal fluctuations in urban emission dynamics. Nevertheless, several limitations and sources of uncertainty should be acknowledged and warrant further investigation. First, carbon emission data are inherently subject to uncertainty, primarily arising from the estimation of emission factors (Liang et al., 2026). Although the CHRED database is constructed using official statistical sources to minimize uncertainty, residual errors inevitably remain. In particular, portions of the dataset rely on gridded emissions estimated through spatial interpolation and proxy-based allocation methods, which may introduce additional uncertainties into city-level emission estimates. Second, the definition of cities in this study is based on administrative boundaries. This approach ensures, to some extent, the comparability of emissions data and development stages between cities. Although administrative boundaries ensure statistical consistency within the national accounting framework, they do not necessarily correspond to functional urban areas or economically integrated metropolitan systems. As a result, the aggregation and ranking of emissions may be influenced by jurisdictional delineations. (Liang et al., 2025; Wang & Chen, 2021). In polycentric urban regions, emissions associated with a single functional system may be distributed across multiple administrative units, potentially increasing fragmentation and affecting the estimated scaling coefficient (Q). Conversely, administrative jurisdictions that encompass extensive suburban or industrial zones may report relatively high total emissions compared to their functional urban cores. Therefore, the estimated Zipf coefficients should be interpreted as reflecting structural patterns within administrative urban systems rather than strictly functional urban hierarchies. To enhance robustness, we incorporated $\pm 5\%$ confidence intervals into the fitting process to account for statistical variability in emission estimates. Across all years and sectors, the Zipf-like scaling relationship remains clearly observable within these intervals, and the classification of Q values exhibits no substantive change. This suggests that moderate estimation uncertainty does not materially alter the identified structural patterns. Alternative delineations, such as functional urban areas or metropolitan regions, may yield different distributional characteristics and merit future exploration. Third, although Zipf's law has been widely applied across diverse research fields, its explanatory power may differ from that of traditional economic principles, and its applicability is not universal (Ectors et al., 2020; Rybski & Ciccone, 2023). Consequently, the observed Zipf-like patterns should be interpreted as empirical regularities rather than deterministic laws. Despite these limitations, this study provides relatively robust and novel insights into the structural regularities of urban carbon emissions. By extending Zipf's law to a multi-sectoral and typology-specific urban emissions framework, the findings offer valuable diagnostic tools and policy-relevant implications for the cyclical optimization and low-carbon transformation of urban development in China and potentially in other rapidly urbanizing economies.

5. Conclusion

This study applies Zipf's law to the analysis of urban CO₂ emissions across multiple economic and functional sectors, including agriculture, industry, services, transportation, and residential activities. By extending the rank-size framework to sector-specific emissions, this approach provides novel insights into the inequality, concentration, and structural regularities of carbon emissions across different stages of urban development.

The results indicate that the majority of Chinese cities (78.47%–80.77%) conform to the ideal state described by Zipf's law, suggesting that urban development and carbon emissions generally operate under a "least-effort" equilibrium. Moreover, the evolution of the Zipf index (Q) reveals that from 2005 to 2020, China's urban development has been progressively optimizing toward a more intensive and sustainable trajectory. Notably, this optimization process appears to be at an early

stage, as the proportion of "High Frequency" cities—representing highly optimized development—remains relatively low at approximately 11.8%.

Carbon emissions from the agricultural and transportation sectors have consistently remained below the emission levels associated with standard urban development. Over the 15-year study period, the proportions of both "Low Frequency" and "High Frequency" cities in the agricultural sector declined, indicating a convergence toward a more balanced emission structure. In contrast, 1.78% of cities in the transportation sector transitioned into the "High Frequency" category. Although the industrial sector as a whole has approached the ideal state described by Zipf's Law ($Q = 1.03 \approx 1$), with an increasing number of "high-frequency" cities, a sectorally disaggregated analysis reveals that substantial optimization potential remains. In particular, the industrial energy sub-sector continues to exhibit persistent deviations from the ideal distribution, with Q -values consistently exceeding 1.14, indicating an overall pattern of extensive development. A similar pattern is observed in the household sector. While residential emissions have, in aggregate, entered a high-intensity development phase, rural household emissions remain markedly misaligned with urban development levels ($Q > 1.12$), with approximately 24.19% of cities classified as "Low Frequency". By contrast, both the service sector and indirect emissions remain in the initial stage of extensive development. The proportion of "High Frequency" cities in these sectors is relatively low, accounting for only 11.8%, highlighting them as priority areas for sustained structural optimization and low-carbon transformation.

Carbon emission patterns exhibit pronounced heterogeneity across different urban typologies. Service-oriented cities have achieved measurable progress but remain largely in the early stage of extensive development. Industrial cities entered a phase of efficient and intensive development at an early stage, although a partial reversal was observed in 2020. Other city types have exhibited a sustained transition toward the advanced stage of low-carbon optimization. The transition toward a service-oriented urban development model constitutes China's dominant long-term development trajectory, with many industrial cities likely to transition first into intermediate urban forms before ultimately evolving into service-oriented cities.

CRediT authorship contribution statement

Sen Liang: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Ke Wang:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation. **Qiu Jin:** Writing – original draft, Visualization, Data curation. **Jianjun Zhang:** Methodology. **Zhenlin Fan:** Data curation. **Iskid Jacquet:** Data curation. **Bangning Fu:** Data curation.

Declaration of competing interest

We certify that we have participated sufficiently in the work and the written paper is entirely original. The underlying data are represented accurately in the paper, and the data or work not belong to this paper has been appropriately cited or quoted as the references. And we also ensure that we don't publish manuscripts describing essentially the same research in more than one journal or primary publication, and we don't submit a previously published paper in another journal. Any obtained data in this paper could be used or reported with permission. We have reviewed the final version of the manuscript and approve it for publication. This paper does not involve any hazard and the use of animal or human subjects.

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Supplementary materials

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Data availability

Data will be made available on request.

References

- Ahmad, S. (2025a). Green technologies, R&D and environmental policies: a dual ARDL-NARDL approach to sustainable transition. *Clean Technologies and Environmental Policy*, 27(11), 7317–7338.
- Ahmad, S. (2025b). Pathways to environmental sustainability in developing Asia: Insights from environmental policy, green innovation and energy structure. *Renewable & Sustainable Energy Reviews*, 216, Article 115646.
- Akhundjanov, S. B., Devadoss, S., & Luckstead, J. (2017). Size distribution of national CO2 emissions. *Energy Economics*, 66, 182–193.
- Appiah-Kubi, M. A., & Gyambibi, F. A. (2025). City size distribution of African countries: A spatial analysis using geospatial data. *Cities*, 160, 105808.
- Arshad, S., Hu, S. G., & Ashraf, B. N. (2018). Zipf's law and city size distribution: A survey of the literature and future research agenda. *Physica a-Statistical Mechanics and Its Applications*, 492, 75–92.
- Arshad, S., Hu, S. G., & Ashraf, B. N. (2019). Zipf's law, the coherence of the urban system and city size distribution: Evidence from Pakistan. *Physica a-Statistical Mechanics and Its Applications*, 513, 87–103.
- Ausloos, M., Nedic, O., Fronczak, A., & Fronczak, P. (2016). Quantifying the quality of peer reviewers through Zipf's law. *Scientometrics*, 106(1), 347–368.
- Batty, M. (2008). The size, scale, and shape of cities. *Science*, 319(5864), 769–771.
- Bevacqua, E., Schleussner, C. F., & Zscheischler, J. (2025). A year above 1.5°C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. *Nature Climate Change*, 15(3), 262–265.
- Cai, B. F., Cui, C., Zhang, D., Cao, L. B., Wu, P. C., Pang, L. Y., ... Dai, C. Y. (2019). China city-level greenhouse gas emissions inventory in 2015 and uncertainty analysis. *Applied Energy*, 253, 113579.
- Chen, H. X., Zhang, X. L., Wu, R. W., & Cai, T. Y. (2020). Revisiting the environmental Kuznets curve for city-level CO2 emissions: based on corrected NPP-VIIRS nighttime light data in China. *Journal of Cleaner Production*, 268, 121575.
- Chen, Y. G. (2012). The mathematical relationship between Zipf's law and the hierarchical scaling law. *Physica a-Statistical Mechanics and Its Applications*, 391(11), 3285–3299.
- Cui, Z. P., Liu, X. M., Lu, S., & Liu, Y. (2024). Dynamic Comprehensive Evaluation of the Development Level of China's Green and Low Carbon Circular Economy under the Double Carbon Target. *Polish Journal of Environmental Studies*, 33(1), 101–115.
- Ectors, J., Kochan, B., Janssens, D., Bellemans, T., & Wets, G. (2020). Zipf's power law in activity schedules and the effect of aggregation. *Future Generation Computer Systems-the International Journal of Esience*, 107, 1014–1025.
- Gouldson, A., Colenbrander, S., Sudmant, A., Papargyropoulou, E., Kerr, N., McAnulla, F., & Hall, S. (2016). Cities and climate change mitigation: Economic opportunities and governance challenges in Asia. *Cities*, 54, 11–19.
- Hackmann, A., & Klarl, T. (2020). The evolution of Zipf's Law for US cities. *Papers in Regional Science*, 99(3), 841–852.
- He, C. F., Pan, F. H., & Chen, T. M. (2016). Research progress of industrial geography in China. *Journal of Geographical Sciences*, 26(8), 1057–1066.
- He, M., Abbasi, B. N., & Fan, Z. C. (2024). Education and technological innovation in mitigating CO2 emissions and fostering green economic growth in China: Marginal effects and policy threshold analyses. *Journal of Environmental Management*, 370, 122786.
- Jia, J. X., Ma, G. R., Qin, C., & Wang, L. Y. (2020). Place-based policies, state-led industrialisation, and regional development: Evidence from China's Great Western Development Programme. *European Economic Review*, 123, 103398.
- Jin, F. J., Ding, J. X., Wang, J. E., Liu, D., & Wang, C. J. (2012). Transportation development transition in China. *Chinese Geographical Science*, 22(3), 319–333.
- Jing, Q. L., Liu, H. Z., Yu, W. Q., & He, X. (2022). The Impact of Public Transportation on Carbon Emissions-From the Perspective of Energy Consumption. *Sustainability*, 14(10), 6248.
- Li, P. F., & Lu, M. (2021). Urban Systems: Understanding and Predicting the Spatial Distribution of China's Population. *China & World Economy*, 29(4), 35–62.
- Liang, S., Wang, K., Duan, W. S., & Ma, Y. H. (2026). Long-term changes in city-level CH4 emissions from rice cultivation in China: Patterns, drivers, projections, and sustainable pathways. *Resources Conservation and Recycling*, 227, 108738.
- Liang, S., Wang, K., Zhang, L., & Li, Y. (2025). Urban boundaries and emission performance: CO2 and air pollutant synergy in China –New practice from Guangzhou City. *Journal of Cleaner Production*, 492, 144928.

- Liang, S., Zhang, J., Cai, B., Wang, K., Zhang, S., & Li, Y. (2024). How to perceive and map the synergy between CO₂ and air pollutants: Observation, measurement, and validation from a case study of China. *Journal of Environmental Management*, 351, 119825.
- Liu, J. X., Qu, J. Y., & Zhao, K. (2019). Is China's development conforms to the Environmental Kuznets Curve hypothesis and the pollution haven hypothesis? *Journal of Cleaner Production*, 234, 787–796.
- Liu, X. Y., Wang, X. E., Song, J. N., Wang, H. N., & Wang, S. O. (2019). Indirect carbon emissions of urban households in China: Patterns, determinants and inequality. *Journal of Cleaner Production*, 241, 118335.
- Liu, Z. Y., Zhang, Y., Ni, X. F., Zhu, J., Zhang, Q. Y., & Wang, J. N. (2023). Climate action may reduce the risk of unemployment: An insight into the city-level interconnections among the sustainable development goals. *Resources Conservation and Recycling*, 194, 107002.
- Lv, G. Y., Zheng, S., & Hu, W. (2022). Exploring the relationship between the built environment and block vitality based on multi-source big data: an analysis in Shenzhen, China. *Geomatics Natural Hazards & Risk*, 13(1), 1593–1613.
- Ma, H. M., Sun, Y. W., Yang, L. X., Li, X. Z., Zhang, Y., & Zhang, F. (2023). Advanced Human Capital Structure, Industrial Intelligence and Service Industry Structure Upgrade—Experience from China's Developments. *Emerging Markets Finance and Trade*, 59(5), 1372–1389.
- Mi, Z. F., Meng, J., Guan, D. B., Shan, Y. L., Song, M. L., Wei, Y. M., ... Hubacek, K. (2017). Chinese CO₂ emission flows have reversed since the global financial crisis. *Nature Communications*, 8, 1–10.
- Muller, N. Z. (2016). Power Laws and Air Pollution. *Environmental Modeling & Assessment*, 21(1), 31–52.
- Muneer, T., Celik, A. N., & Caliskan, N. (2011). Sustainable transport solution for a medium-sized town in Turkey-A case study. *Sustainable Cities and Society*, 1(1), 29–37.
- Qi, Z. L., Zheng, Y. X., Cao, W. X., Liu, Y. X., Li, X., Fei, Y. Y., ... Wang, J. N. (2025). Weakening synergies in carbon and air pollution co-control necessitate robust structural transitions in China's transportation sector. *National Science Review*, 12(11), 186–201.
- Ridzuan, N., Marwan, N. F., Khalid, N., Ali, M. H., & Tseng, M. L. (2020). Effects of agriculture, renewable energy, and economic growth on carbon dioxide emissions: Evidence of the environmental Kuznets curve. *Resources Conservation and Recycling*, 160, 104879.
- Rybski, D., & Ciccone, A. (2023). Auerbach, Lotka, and Zipf: pioneers of power-law city-size distributions. *Archive for History of Exact Sciences*, 77(6), 601–613.
- Sarkodie, S. A., Owusu, P. A., & Leirvik, T. (2020). Global effect of urban sprawl, industrialization, trade and economic development on carbon dioxide emissions. *Environmental Research Letters*, 15(3), 12.
- Shen, C. F., Zhang, J., Pang, J. F., & Xu, H. F. (2024). Study on industrial carbon emissions in China based on GDIM decomposition method and two decoupling effects. *Environmental Science and Pollution Research*, 31(10), 15648–15670.
- Shuai, C. Y., Chen, X., Shen, L. Y., Jiao, L. D., Wu, Y., & Tan, Y. T. (2017). The turning points of carbon Kuznets curve: Evidence from panel and time-series data of 164 countries. *Journal of Cleaner Production*, 162, 1031–1047.
- Sodiq, A., Baloch, A. A. B., Khan, S. A., Sezer, N., Mahmoud, S., Jama, M., & Abdelaal, A. (2019). Towards modern sustainable cities: Review of sustainability principles and trends. *Journal of Cleaner Production*, 227, 972–1001.
- Soo, K. T. (2005). Zipf's Law for cities: a across-country investigation. *Regional Science and Urban Economics*, 35(3), 239–263.
- Tollefson, J. (2025). Earth breaches 1.5°C climate limit for the first time: what does it mean? *Nature*, 637(8047), 769–770.
- Wang, C. H., & Lin, B. Q. (2023). Assessing the Impact of Regional Industrial Relocation in China: Based on the Information Taken From a Multi-Regional Input-Output Analysis. *Journal of Global Information Management*, 31(1), 1–26.
- Wang, D., Cheng, H. B., Wang, P., Huang, X. Y., & Jian, G. P. (2017). Zipf's Law in Passwords. *IEEE Transactions on Information Forensics and Security*, 12(11), 2776–2791.
- Wang, D. H., Li, M. H., & Di, Z. R. (2005). True reason for Zipf's law in language. *Physica A-Statistical Mechanics and Its Applications*, 358(2-4), 545–550.
- Wang, H. K., Lu, X., Deng, Y., Sun, Y. G., Nielsens, C. P., Li, Y. F., ... McElroy, M. B. (2019a). China's CO₂ peak before 2030 implied from characteristics and growth of cities. *Nature Sustainability*, 2(8), 748–754.
- Wang, J. J., & Chen, Y. G. (2021). Economic Transition and the Evolution of City-Size Distribution of China's Urban System. *Sustainability*, 13(6), 3287.
- Wang, Q. S., Liu, M. Q., Tian, S., Yuan, X. L., Ma, Q., & Hao, H. L. (2021). Evaluation and improvement path of ecosystem health for resource-based city: A case study in China. *Ecological Indicators*, 128, 107852.
- Wang, Y. F., Lyu, J., Liang, X., Luo, C. H., Ma, X. N., Li, J., Li, Q., Zheng, L. N., & Guan, Q. F. (2024). Using Zipf's Law to Optimize Urban Spatial Layouts in an Urban Agglomeration Area. *Annals of the American Association of Geographers*, 114(6), 1342–1364.
- Wang, Y. J., Sun, Q. Q., Wu, J. J., Han, S., Zhang, R. A., Jiang, S. Y., & Gu, X. (2023). Research on the low carbon development path of China's coal industry under carbon peaking & carbon neutral target: Based on the RCPs-SSPs framework. *Resources Policy*, 86, 104091.
- Wang, Y. N., Luo, X. Y., Chen, W., Zhao, M. J., & Wang, B. W. (2019b). Exploring the spatial effect of urbanization on multi-sectoral CO₂ emissions in China. *Atmospheric Pollution Research*, 10(5), 1610–1620.
- Wang, Y. Y., & Sun, B. D. (2024). The types of city size distributions and their evolution. *Cities*, 150, 105045.
- Wei, J., Zhang, J. J., Cai, B. F., Wang, K., Liang, S., & Geng, Y. H. (2021). Characteristics of carbon dioxide emissions in response to local development: Empirical explanation of Zipf's law in Chinese cities. *Science of the Total Environment*, 757, 143912.
- Wiedmann, T., & Allen, C. (2021). City footprints and SDGs provide untapped potential for assessing city sustainability. *Nature Communications*, 12(1), 3758.
- Wu, C. F., Li, G., Yue, W. Z., Lu, R. C., Lu, Z. W., & You, H. Y. (2015). Effects of Endogenous Factors on Regional Land-Use Carbon Emissions Based on the Grossman Decomposition Model: A Case Study of Zhejiang Province, China. *Environmental Management*, 55(2), 467–478.
- Wu, Y. Z., Jiang, M. Y., Chang, Z. J., Li, Y. Q., & Shi, K. F. (2020). Does China's Urban Development Satisfy Zipf's Law? A Multiscale Perspective from the NPP-VIIRS Nighttime Light Data. *International Journal of Environmental Research and Public Health*, 17(4), 1460.
- Yang, X., Wang, X. C., & Zhou, Z. Y. (2018). Development path of Chinese low-carbon cities based on index evaluation. *Advances in Climate Change Research*, 9(2), 144–153.
- Yao, X. L., Kou, D., Shao, S., Li, X. Y., Wang, W. X., & Zhang, C. T. (2018). Can urbanization process and carbon emission abatement be harmonious? New evidence from China. *Environmental Impact Assessment Review*, 71, 70–83.
- Zhang, J., Li, C. L., Zhang, B. L., Hu, Y. M., Wang, H., Li, Z. X., & Zhang, Q. (2024). Spatiotemporal Evolution and Rank-Size Pattern of Chinese Urban Settlements. *Remote Sensing*, 16(1), 19.
- Zhang, M., Chang, I. S., & Wu, J. (2025). Comprehensive assessment of low-carbon development and exploration of low-carbon transformation paths in Chinese cities. *Clean Technologies and Environmental Policy*, 27(11), 7297–7315.
- Zhang, Y. G., Wang, X. H., Ye, Y., Wang, L. S., Zhang, Y. F., & Yao, S. M. (2025). Spatially heterogeneous impacts of urban vitality on carbon emissions: A multi-source data-driven mechanistic analysis. *Sustainable Cities and Society*, 130, 106622.
- Zhou, L. Z., Tong, G. J., Qi, J. G., & He, L. (2024). Demand Potential for Agricultural Trade between China and Countries along the "Belt and Road". *Food*, 13(19), 3210.
- Zhou, Y., Chen, M. X., Tang, Z. P., & Mei, Z. A. (2021). Urbanization, land use change, and carbon emissions: Quantitative assessments for city-level carbon emissions in Beijing-Tianjin-Hebei region. *Sustainable Cities and Society*, 66, 102701.