

Article

Development-Stage Differences in Land-Use Carbon Effects of China's Resource-Based Cities: Spatiotemporal Evolution and Driving Mechanisms

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Abstract

In the context of global climate change and China's dual-carbon strategy, this analysis examines how land-use transition is associated with land-use carbon effects in China's resource-based cities. From the perspective of urban development stages, an analytical framework is built by linking development stage, land-use structure, and carbon source–sink structure. Using 262 resource-based cities from 2011 to 2023, we estimate land-use-related carbon emissions, carbon sequestration, and net land-use carbon effects with the carbon emission coefficient method and analyze their spatiotemporal patterns and driving factors using GeoDetector. The results show clear differences among city types. Mature cities form the largest group. Growth cities show the fastest expansion of impervious surfaces, while regenerative cities present signs of ecological recovery. This suggests that land-use transition is not simply the expansion of impervious surfaces, but a stage-dependent process of structural change. Land-use carbon effects also differ across stages. Mature cities maintain high and stable carbon-source effects. Growth cities exhibit increasing carbon-source effects, declining cities show reduced emissions but limited improvement in the carbon source–sink structure, and regenerative cities show improved carbon-sink capacity under ecological restoration. Overall, net land-use carbon effects follow a rise–decline–rebound pattern and show clear spatial heterogeneity and visually apparent clustering patterns. Population size has strong explanatory power, while interactions between socioeconomic and land-use factors further shape spatial differences. These results support stage-specific low-carbon transition strategies.

Keywords: resource-based cities; land-use transition; carbon source–sink structure; land-use carbon effects; urban development stages; spatial differentiation



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1. Introduction

Global climate change has made carbon mitigation a continuing concern in environmental governance. China's dual-carbon strategy has also placed low-carbon transition within the broader agenda of economic restructuring, energy transition, and spatial governance [1,2]. Land use is closely involved in this process. It provides space for urban growth, industrial activities, and infrastructure construction, while also affecting carbon emissions, carbon sequestration, and the balance between them. Existing studies have

shown that land-use and land-cover change (LUCC) can reshape terrestrial carbon fluxes by altering vegetation cover, ecosystem restoration, and the spatial distribution of human activities [3–6]. Urban expansion may further influence carbon pools and carbon-emission patterns through changes in built-up land, urban form, and land-use intensity [7–9]. At the same time, long-term land-cover datasets and impervious-surface products have improved the observation of land-use transition over large regions and extended time periods [10–13]. These studies provide a basis for analyzing land-use carbon effects through changes in land-use structure. Recent studies have further examined land-use carbon emissions at county and city scales, including spatiotemporal effects, scenario simulation, and spatial association networks [14–17].

Resource-based cities are a relevant urban group for discussing this relationship. Their development has long been associated with mineral extraction, energy production, and primary processing, and land-use change in these cities is often intertwined with industrial adjustment and urban transformation. Existing research has examined their low-carbon transition from several perspectives. Fan et al. [18] investigated how natural resource dependence is related to low-carbon emission efficiency in Chinese cities. Yu et al. [19] found that policies targeting resource-exhausted cities contributed to improvements in local energy efficiency, while Ai et al. [20] reported that such policies were associated with carbon-emission reductions. Wu et al. [21] examined whether the emissions trading system helped reduce carbon emissions in resource-based cities. Wang et al. [22] analyzed the effect of sustainable development planning on corporate ESG performance in these areas. Gao and He [23] linked the digital economy, urban carbon emissions, and land-resource misallocation. Li et al. [24] evaluated green land-use efficiency in resource-based cities and identified its spatiotemporal variation. Recent studies have also examined green land-use efficiency under carbon-emission constraints, with attention to resource-based cities and those in the Yellow River Basin [25,26]. Lu et al. [27] assessed the effects of external technology and investment on their low-carbon transition, and Feng et al. [28] examined the transformation of resource-based cities through firms' carbon-emission reductions. Hou et al. [29] analyzed the coordination between green expansion and carbon reduction under sustainable development policies. Studies more directly related to land-use carbon effects have also emerged. Wu et al. [30] assessed land-use carbon emissions in a coal-dependent city, while Li et al. [31] discussed sustainable municipal energy-system transition in Tangshan. Yin et al. [32] evaluated the green transformation efficiency of mineral resource-based cities. These studies clarify the roles of policy intervention, resource dependence, land-resource allocation, and transformation pathways. However, many of them focus on carbon emissions, policy effects, efficiency, or urban transformation as separate issues. The relationship among land-use restructuring, carbon-source effects, carbon-sink effects, and net land-use carbon effects has received less direct attention. Development-stage differences among growth, mature, declining, and regenerative cities are also not always considered together with land-use carbon effects. Recent research has further emphasized that urbanization patterns and population distribution in China are shaped not only by demographic and economic forces but also by state-led territorial governance, including hukou reform, balanced regional-development strategies, and sustainable urbanization policies [33]. This perspective suggests that the population should not be understood merely as a demographic scale variable. Its spatial concentration, mobility, and associated demand for urban and industrial land are also shaped by institutional arrangements and territorial-governance strategies, which may produce different land-use and carbon consequences across urban development stages. Nevertheless, existing studies on resource-based cities generally examine population size, land-use change, and carbon emissions as separate dimensions. Limited attention has been paid to how institutionally shaped population

distribution interacts with stage-specific land-use restructuring and, in turn, affects the carbon source–sink structure. This missing linkage limits a fuller understanding of the spatial differentiation of land-use carbon effects in resource-based cities.

To address this gap, we develop an analytical framework linking the development stage, land-use structure, and carbon source–sink structure. The empirical investigation covers 262 resource-based cities in China and compares land-use carbon effects across different stages of urban development. Specifically, it assesses how land-use transitions, carbon-source effects, carbon-sink effects, and net land-use carbon effects differ across development stages, and how socioeconomic and land-use factors independently and interactively explain the spatial differentiation of net land-use carbon effects. Accordingly, although population size is used as the empirical indicator, its role is interpreted within the broader institutional and territorial context shaping population agglomeration and land demand. The analytical design has three main features. First, it introduces development-stage differences into the analysis of land-use carbon effects in resource-based cities, allowing growth, mature, declining, and regenerative cities to be compared within the same analytical frame. Second, it considers carbon emissions, carbon sequestration, and net land-use carbon effects together, which helps describe how land-use restructuring is reflected in the carbon source–sink structure. Third, it examines the joint influence of socioeconomic and land-use variables, rather than interpreting spatial differentiation through isolated factors alone. In this way, the analysis captures differences among resource-based cities and the land-use processes associated with their land-use carbon effects. Although the land-use transition matrix, carbon emission coefficient method, and GeoDetector are established analytical approaches, the contribution does not lie in proposing a new individual method. Instead, it lies in integrating the official development-stage classification, the assessment of carbon-source effects, carbon-sink effects, and net land-use carbon effects, and GeoDetector interaction analysis within a unified city-level framework. Meanwhile, standardized carbon coefficients may not fully capture regional heterogeneity, and GeoDetector identifies spatial associations rather than causal relationships; these analytical boundaries are therefore considered when interpreting the results.

The rest of this paper is structured as follows. Section 2 describes the research framework, study area, data, and methods. Section 3 presents the empirical results. Section 4 discusses the relationship between land-use transition and land-use carbon effects in resource-based cities. Section 5 summarizes the main conclusions and policy implications.

2. Research Framework

2.1. Research Objects and Analytical Approach

The analysis centers on resource-based cities in China. They are defined as urban areas whose formation and development have long been shaped by the development and use of natural resources, and whose economic growth depends heavily on mineral extraction and related processing industries. According to their development stage, these cities are classified as growth, mature, declining, or regenerative cities. Considerable variation exists among these development stages in terms of resource-exploitation intensity, industrial evolution trajectories, land-use patterns, and carbon source–sink structures. Therefore, a stage-based perspective helps clarify the explanatory patterns of land-use carbon effects. The definitions of relevant concepts are provided in Table 1.

Table 1. Definitions of key terms for resource-based cities and their development stages.

Concept	Core Definition
Resource-based cities	A resource-based city refers to an urban area whose formation and development have been strongly shaped by the extraction and processing of natural resources, including mineral and energy resources, and whose economic and industrial structures have historically shown a relatively high degree of resource dependence.
Growth cities	A growth city refers to a resource-based city in which resource development remains in an expanding stage, resource-support potential is relatively strong, and population, industries, and urban construction activities continue to develop.
Mature cities	A mature city refers to a resource-based city in which resource development has entered a relatively stable stage, resource-support capacity remains strong, and the resource-based industrial system and urban spatial structure are comparatively well established.
Declining cities	A declining city refers to a resource-based city in which recoverable resources are decreasing, traditional resource-based industries are weakening, and the city faces increasing pressure to develop alternative industries and improve its sustainable-development capacity.
Regenerative cities	A regenerative city refers to a resource-based city in which dependence on resource extraction has been substantially reduced and substantial progress has been made in economic restructuring, industrial diversification, and urban transformation.

The development-stage classification adopted here follows the National Sustainable Development Plan for Resource-Based Cities (2013–2020) [34]. The official classification is based primarily on resource-support capacity and socioeconomic sustainable-development capacity, rather than on carbon-emission performance. The classification published in the plan is treated as an exogenous and time-invariant grouping and is applied consistently to all observations from 2011 to 2023, including the 2011 baseline year. Therefore, the carbon-source effects, carbon-sink effects, and net land-use carbon effects identified in the subsequent analysis are empirical outcomes rather than criteria used to classify the cities. This treatment facilitates intertemporal comparison, although it does not capture possible transitions between development stages after the classification was issued.

Here, land-use carbon effects are defined as the combined impacts of land-use conversion, structural adjustment, and changes in spatial configuration on carbon emissions and carbon sequestration. The conversion to impervious surfaces generally reinforces carbon-source effects. In contrast, changes in ecological land, such as forest, grassland, and water bodies, have a more direct effect on regional carbon-sequestration capacity. Therefore, land-use change involves not only variations in land-use scale and structure but also the reconfiguration of the carbon source–sink structure.

For terminological consistency, “land-use carbon effects” is used as the overarching term throughout the manuscript. “Carbon-source effects” refer to positive carbon emissions, whereas “carbon-sink effects” refer to carbon sequestration and are represented by negative values. “Net land-use carbon effects” denote the algebraic sum of carbon-source and carbon-sink effects. A positive net value indicates a net carbon-source effect, whereas a negative net value indicates a net carbon-sink effect. The term “carbon source–sink structure” is used consistently to describe the relative composition of carbon-source and carbon-sink effects. Conceptually, the framework draws on four complementary perspectives. Land-use dynamics and urbanization guide the identification of changes in land-use scale, structure, and conversion pathways across different development stages. Urban metabolism provides the basis for linking the concentration of energy-consuming activities on impervious surfaces with carbon-source effects, while changes in ecological land are interpreted in relation to regional carbon-sink capacity [35]. The socio-ecological transition perspective is used to compare how resource-based cities at different development stages shift among

resource-dependent expansion, industrial restructuring, and ecological restoration [36]. Urban political ecology provides an interpretive lens for understanding how institutional governance, population agglomeration, land demand, and uneven territorial development shape stage-specific land-use outcomes [37]. These perspectives are not treated as separate empirical models; rather, they guide the selection of analytical dimensions and variables and support the interpretation of differences in land-use transition and carbon source–sink structures across development stages.

Building on these operational links, development-stage differences, land-use structural change, and adjustments in the carbon source–sink structure are integrated into a unified analytical framework. The development stage provides the contextual basis for differentiating urban transformation trajectories, the land-use structure serves as the key link between urban development and land-use carbon effects, and the carbon source–sink structure reflects the resulting balance between carbon emissions and carbon sequestration. Accordingly, the framework examines how land-use transitions vary across development stages and how these transitions are associated with changes in carbon-source effects, carbon-sink effects, and net land-use carbon effects.

2.2. Study Area and Characteristics of Resource-Based Cities

The analysis uses data from 262 resource-based cities in China as the basis for analysis. The study area covers eastern, central, western, and northeastern China and is therefore broadly representative at the national level. The classification of resource-based cities is based on the National Sustainable Development Plan for Resource-Based Cities (2013–2020) [38]. Figure 1 shows the spatial distribution of resource-based cities across different development stages.

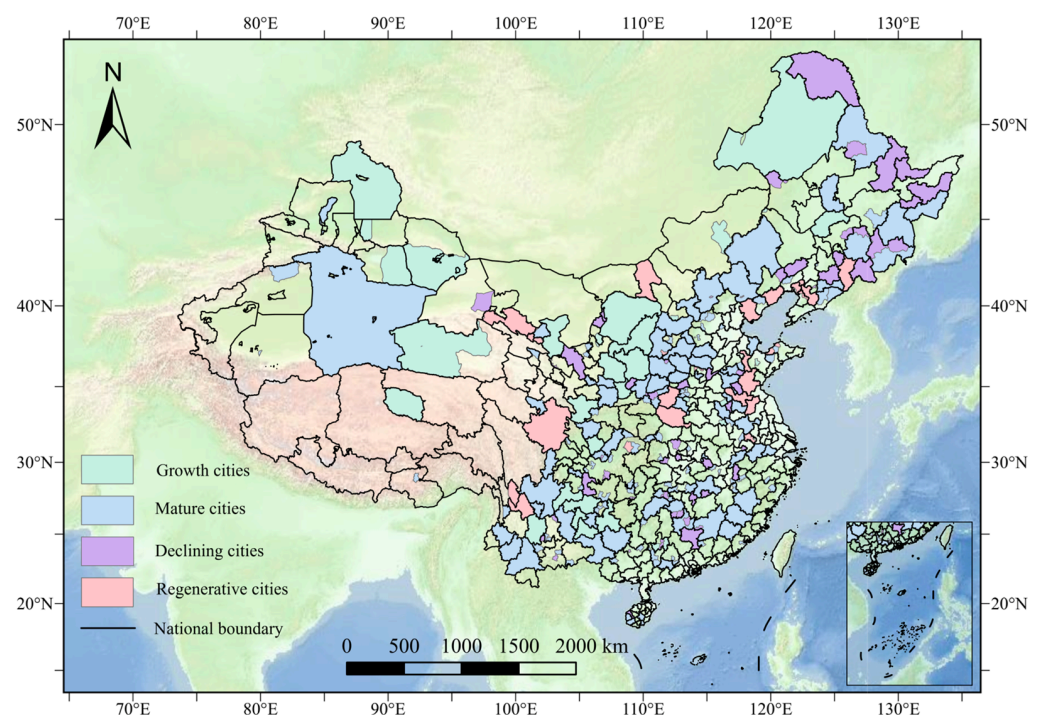


Figure 1. Spatial distribution of the 262 resource-based cities in China by development stage.

From the perspective of sample composition, mature cities account for the largest share, with 141 cities (53.82%), and thus constitute the dominant type. Declining and growth cities account for 25.57% and 11.83% of the sample, respectively, while regenerative cities represent the smallest proportion, at 8.78%. In spatial terms, significant regional differences are evident across the four types. Mature cities are widely distributed across

the country, whereas declining cities are concentrated mainly in northeast China and parts of central China. Growth cities are primarily located in western China, especially in Inner Mongolia and Xinjiang. In contrast, regenerative cities are relatively few in number and exhibit a scattered spatial distribution, mainly in northeast, eastern, and central China.

2.3. Research Content and Technical Route

To examine land-use transitions and associated land-use carbon effects across different development stages, the analysis proceeds along three dimensions: land-use change, land-use carbon-effect evaluation, and driving-factor analysis. First, it analyzes changes in land-use scale, structural evolution, and conversion relationships across city types to identify differences in land-development intensity, directions of spatial expansion, and land-use transition pathways [37,39]. Second, based on the land-use analysis, it estimates land-use carbon emissions, carbon sequestration, and net land-use carbon effects, paying particular attention to changes in carbon source–sink structure and patterns of spatial differentiation. Finally, by incorporating socioeconomic conditions, industrial development, population agglomeration, land-use allocation, and spatial location, it examines which socioeconomic and land-use factors help explain the spatial differentiation of net land-use carbon effects.

Building on the above research content, the analytical route consists of research-object identification and stage classification, land-use change analysis, land-use carbon-effect measurement, and driving-factor analysis (Figure 2). First, it identifies the study objects and classifies resource-based cities into different development stages according to relevant plans and classification standards. It then integrates land-use products, socioeconomic data, and geographic information to analyze land-use change across city types. Subsequently, drawing on the land-use results, it estimates carbon emissions, carbon sequestration, and net land-use carbon effects across different land-use types, thereby characterizing the carbon source–sink structure and its evolution. Finally, it incorporates relevant driving factors to compare the explanatory patterns of land-use carbon effects. Through this technical route, the analysis progresses from phenomenon identification to effect measurement and then to driving-factor interpretation.

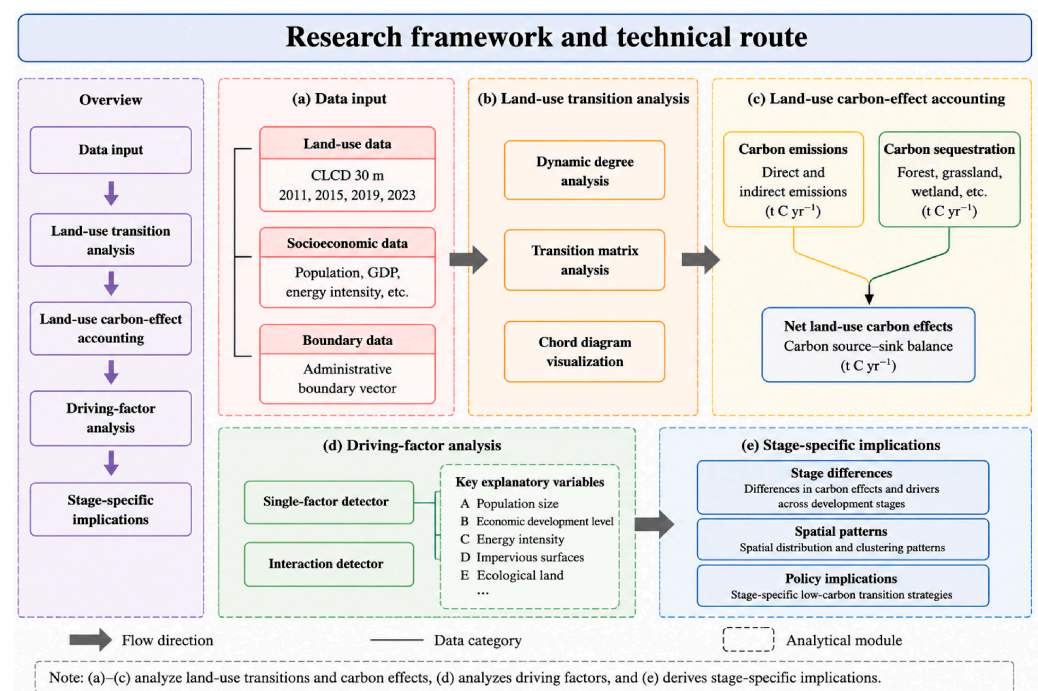


Figure 2. Research framework and technical route.

2.4. Data and Methods

2.4.1. Data Sources

Land-use, socioeconomic, and geographic data are combined to analyze land-use change, measure land-use carbon effects, and examine the factors associated with their spatial differentiation. The land-cover data were obtained from Version 1.0.4 of the 30 m annual China Land Cover Dataset (CLCD), developed by Jie Yang and Xin Huang at Wuhan University. This updated dataset provides annual land-cover data for China from 1985 to 2024 [40]. Four annual layers corresponding to 2011, 2015, 2019, and 2023 were selected for the analysis. The methodological framework, classification system, and accuracy assessment of the CLCD were described in the original data publication by Yang and Huang [10]. The CLCD contains nine land-cover classes: cropland, forest, shrub, grassland, water, snow/ice, barren land, impervious surfaces, and wetland. The specific treatment of these land-cover classes in the carbon-accounting procedure is described in Section 2.4.2.

The CLCD raster layers were processed in an Albers Equal Area Conic projection based on the World Geodetic System 1984 (WGS 84), and the administrative boundary data were reprojected to the same coordinate reference system before spatial analysis and area calculation. To ensure temporal comparability, the same prefecture-level administrative boundaries based on the 2013 administrative configuration were used for all four study years. Socioeconomic data, including population size, gross domestic product, and energy intensity, were obtained mainly from national, provincial, and municipal statistical yearbooks. Missing observations were first checked against alternative official sources, and linear interpolation was applied only to isolated internal gaps with valid values in adjacent years; no extrapolation was performed. Because interpolation indicators were not separately retained during the initial data compilation, the exact number and proportion of interpolated observations could not be reliably reconstructed.

2.4.2. Research Methods

(1) Land-Use Transition Analysis

We use data from 2011 to 2023 to construct a land-use transition matrix, which is used to identify the direction and magnitude of conversions among land-use types [37]. On this basis, chord diagrams are used to visualize the main transition pathways, thereby revealing the principal directions of structural change in land use and the stage-specific differences among city types.

(2) Land-Use Dynamic Degree

To characterize land-use variation patterns and the intensity of overall structural change, the analysis employs both the single and comprehensive land-use dynamic degrees. The former measures the average annual rate of area change of a given land-use type during the study period. It is calculated as follows:

$$K = \frac{U_j - U_i}{U_i} \times \frac{1}{T} \times 100\% \quad (1)$$

where K denotes the single land-use dynamic degree; U_i and U_j represent the areas of a given land-use type in the initial and final years of the study period, respectively; and T represents the duration of the study period in years.

The comprehensive land-use dynamic degree measures the overall intensity of land-use structural change in the study area. It is calculated as follows:

$$L = \frac{\sum_{i=1}^n |U_j - U_i|}{\sum_{i=1}^n U_i} \times \frac{1}{T} \times 100\% \quad (2)$$

where L denotes the comprehensive land-use dynamic degree; n is the number of land-use types; and the remaining symbols are defined as above.

(3) Accounting for Land-Use Carbon Effects

The accounting framework estimates land-use carbon effects rather than providing a complete inventory of urban greenhouse gas emissions. From the perspective of land-use structure, these effects are quantified through two components: direct carbon effects of ecological and agricultural land, and indirect carbon emissions associated with impervious surfaces. The effects of non-impervious land-use types are quantified based on the carbon emission coefficient method, whereas those of impervious surfaces are represented by indirect carbon emissions associated with energy consumption [41–44].

The conversion factor of 44/12 was not applied in the carbon-accounting process. Therefore, all calculated land-use carbon effects represent the mass of carbon and are expressed in tons of carbon (t C), rather than tons of CO₂ or tons of CO₂ equivalent. The land-use carbon coefficients are treated as annual coefficients, and the resulting carbon effects represent annual carbon emissions or sequestration.

1. Direct Land-Use Carbon Effects

For land-use types other than impervious surfaces, direct land-use carbon effects are estimated using the carbon emission coefficient method:

$$E_{direct} = \sum_i S_i \times c_i \quad (3)$$

where E_{direct} denotes annual direct land-use carbon effects, expressed in t C yr^{−1}; S_i represents the area occupied by the i -th land-use type, expressed in ha; c_i represents the corresponding annual carbon emission or sequestration coefficient, expressed in t C ha^{−1} yr^{−1}. According to previous studies on the carbon balance of China's terrestrial ecosystems, Table 2 lists the carbon emission coefficients for different land-use types, where positive values represent carbon sources, while negative values represent carbon sinks [41,45]. Because these coefficients represent annual carbon effects per unit area, no additional annualization factor is applied.

Table 2. Annual carbon emission and sequestration coefficients for different non-impervious land-use types (t C ha^{−1} yr^{−1}).

Category	Annual Carbon Coefficient
Cropland	0.420
Forest	−0.578
Shrub	−0.578
Grassland	−0.021
Water	−0.252
Snow/Ice	−0.252
Barren	−0.005
Wetland	−0.252

2. Indirect Land-Use Carbon Effects

Impervious surfaces do not directly generate carbon emissions; however, their expansion usually corresponds to a concentration of energy-consuming activities and energy-related carbon emissions [44,46]. Indirect carbon emissions are estimated from energy consumption and calculated as follows:

$$E_{indirect} = \sum_j E_j \times \alpha_j \times \beta_j \quad (4)$$

where $E_{indirect}$ denotes annual indirect carbon emissions, expressed in t C yr^{-1} ; E_j represents the consumption of the j -th energy type; α_j is the standard coal conversion coefficient; and β_j is the carbon emission coefficient, expressed in t C tce^{-1} . As listed in Table 3, the relevant parameters are taken from the IPCC Guidelines for National Greenhouse Gas Inventories [47] and the China Energy Statistical Yearbook. The energy-related carbon emissions are calculated at the city level and are used to represent the indirect carbon-source effect associated with energy-consuming activities concentrated on impervious surfaces.

Table 3. Standard coal conversion coefficients and carbon emission coefficients by energy type.

Type of Energy	Standard Coal Coefficient (tce t ^{−1})	Carbon Emission Coefficient (t C tce ^{−1})
Raw coal	0.7143	0.7559
Coke	0.9714	0.8550
Crude oil	1.4286	0.5758
Gasoline	1.4714	0.5538
Kerosene	1.4714	0.5714
Diesel oil	1.4571	0.5921
Fuel oil	1.4286	0.6185

Note: The carbon emission coefficients represent the mass of carbon rather than the mass of CO₂. Therefore, the conversion factor of 44/12 is not included. The units kgce kg^{−1} and tce t^{−1} are numerically equivalent.

3. Net Land-Use Carbon Effects

Net land-use carbon effects are calculated as the algebraic sum of direct land-use carbon effects and indirect energy-related carbon emissions, as follows:

$$C_{net} = E_{direct} + E_{indirect} \quad (5)$$

where C_{net} denotes the annual net land-use carbon effect, expressed in t C yr^{-1} . Because the carbon-sequestration coefficients of carbon-sink land-use types are assigned negative values, carbon sequestration is algebraically offset against positive carbon emissions. A positive value of C_{net} indicates a net carbon-source effect, whereas a negative value indicates a net carbon-sink effect.

On this basis, the analysis further examines the carbon source–sink structure and its spatiotemporal differences across development stages. The resulting estimates mainly reflect variations in the land-use carbon effects associated with changes in land-use structure. Therefore, these estimates should not be directly compared with comprehensive urban greenhouse-gas inventories that include additional sectors and non-CO₂ greenhouse gases.

(4) Analysis of Driving Factors

Before applying GeoDetector, continuous driving factors were discretized into categorical strata using the Jenks natural breaks method. For each factor, a common set of classification thresholds was applied to all four study years to ensure temporal comparability. This treatment helps the GeoDetector model detect spatially stratified heterogeneity and compare the explanatory power of different factors. We apply the GeoDetector model to examine the drivers of net land-use carbon effects and their spatial differentiation. It

measures the explanatory power of each factor and analyzes interactions among factors [48]. GeoDetector is effective in identifying the explanatory strength of categorical variables for spatial differentiation and is also suitable for detecting how interactions among multiple factors influence the spatial distribution of the dependent variable. Drawing on related studies and the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) analytical framework, three socioeconomic variables are selected: population size (A), economic development level measured by total gross domestic product (B), and energy intensity (C) [49–51]. Total GDP is used to represent the overall scale of regional economic activity rather than per capita affluence. It also introduces two land-use structural variables: the proportion of impervious surfaces (D) and the proportion of ecological land (E). Together, these variables reflect the combined effects of population agglomeration, economic development, energy use, and changes in land use on net land-use carbon effects. Table 4 describes the driving factors. Single-factor and interaction detection are used to assess the explanatory power of individual factors and factor combinations for spatial differences in net land-use carbon effects. Interaction detection is further employed to determine whether combinations of different driving factors strengthen or weaken the observed spatial differentiation.

Table 4. Description of driving factor variables.

Code	Factor	Indicator	Interpretation
A	Population size	Resident population	Population agglomeration
B	Economic development level	Total gross domestic product (GDP)	Overall scale of regional economic activity
C	Energy intensity	Energy consumption per unit of GDP	Energy-use intensity
D	Impervious surfaces	Proportion of impervious surface area	Construction intensity
E	Ecological land	Proportion of ecological land area	Ecological space configuration

2.4.3. Methodological Scope and Limitations

Several methodological limitations should be considered. First, the standardized carbon coefficients are annual average values and may not fully capture regional differences in natural conditions, ecosystem characteristics, and land-management practices. A formal coefficient-sensitivity analysis was not conducted because consistent region-specific uncertainty ranges were unavailable; therefore, the estimated values should be interpreted primarily for comparative purposes rather than as absolute estimates. Second, the GeoDetector variables were limited by data availability and did not directly include institutional policies, technological progress, or territorial governance indicators. In addition, city-level energy-related emissions were used as a proxy for the carbon-source effect associated with impervious surfaces, and the prefecture-level analytical scale may mask differences within individual cities. Third, as clarified in Section 2.4.1, observation-level interpolation flags were not retained, and the influence of interpolated observations could not therefore be separately quantified. These limitations restrict causal interpretation and absolute precision but do not prevent comparisons across development stages under the same data-processing and carbon-accounting framework.

3. Results and Analysis

3.1. Land-Use Structural Change in Resource-Based Cities

To characterize land-use transition patterns across different city types, we analyze these patterns along three dimensions: rate of change (dynamic degree), magnitude of change (area change), and complexity of change (transition-pathway structure).

3.1.1. Rate of Land-Use Change

During 2011–2023, resource-based cities experienced marked changes in land-use structure, with clear differences in the rate of change across city types. Regenerative cities had the highest comprehensive land-use dynamic degree, reaching 0.16%, indicating that adjustments in their land-use structure were relatively more active. By contrast, those of mature, declining, and growth cities ranged from 0.11% to 0.12%, indicating relatively stable overall change. Overall, land-use structural adjustment was more pronounced in regenerative cities, whereas the other three types showed a relatively similar extent of change. However, the index captures the pace of land-use variation and is insufficient for fully describing the transition pathways and structural features across land-use categories. The land-use transition matrix is therefore used for further analysis.

3.1.2. Patterns of Land-Use Transformation

Land-use transition patterns of different city types from 2011 to 2023 are presented in Figure 3. Overall, all city types showed a common tendency for cropland and part of the ecological land to be converted into impervious surfaces, although the specific transition pathways varied substantially across stages. Among these changes, the conversion from cropland to impervious surfaces was the dominant pathway across all city types.

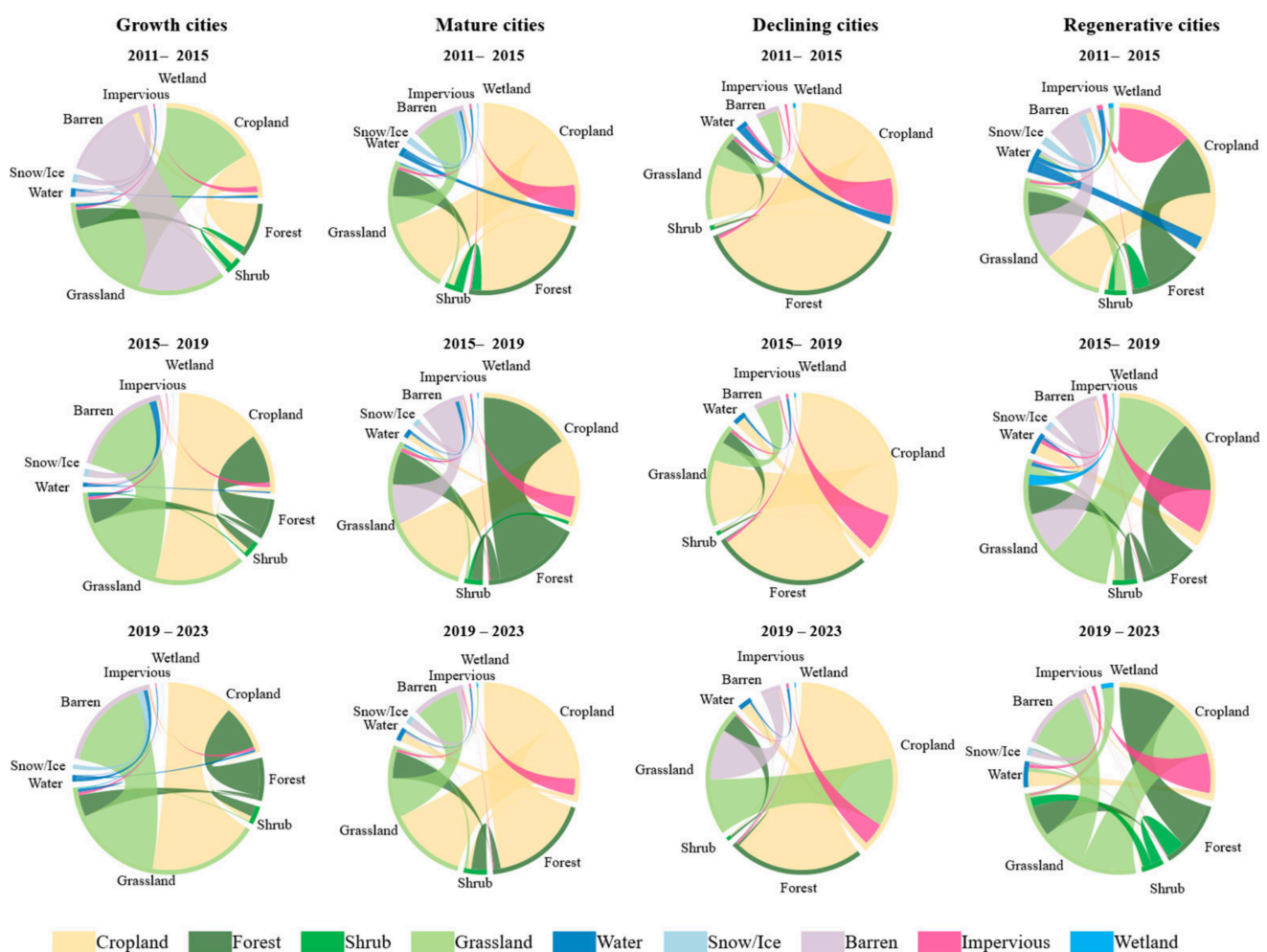


Figure 3. Land-use transition characteristics by resource-based city type, 2011–2023. The color of each link is consistent with that of its source node, and self-loop relationships are excluded.

Specifically, the dominant transition pathway in growth cities is the conversion of cropland to impervious surfaces. However, substantial net area changes also occur within ecological land, particularly through forest expansion and decreases in grassland and shrub. Thus, the dominant conversion pathway is relatively concentrated, whereas the overall area-change structure is more dispersed. In mature cities, in addition to cropland conversion, ecological land such as forest and grassland also participates in land-use adjustment, resulting in more diverse transition pathways than in growth cities. Land-use transition pathways in declining cities are likewise relatively concentrated, with cropland-to-construction-land conversion remaining the dominant form of land-use change. By contrast, regenerative cities exhibit more diverse land-use transition types, with richer inter-conversions among multiple land-use categories, reflecting a higher degree of structural complexity in land-use transitions. Overall, transition relationships are more diverse in mature and regenerative cities, whereas growth and declining cities show more concentrated transition pathways and lower structural complexity.

3.1.3. Land-Use Change Structure

Marked differences are observed among city types in both the scale and structure of land-use change (Figure 4; Table 5), while the complete land-use change statistics are reported in Table A1. Regarding the contribution structure of land-use change (Figure 4), grassland, forest, and cropland are the major contributors across all city types. However, impervious surfaces make a relatively larger contribution in mature and regenerative cities, showing that construction land change plays a key role in land-use adjustment.

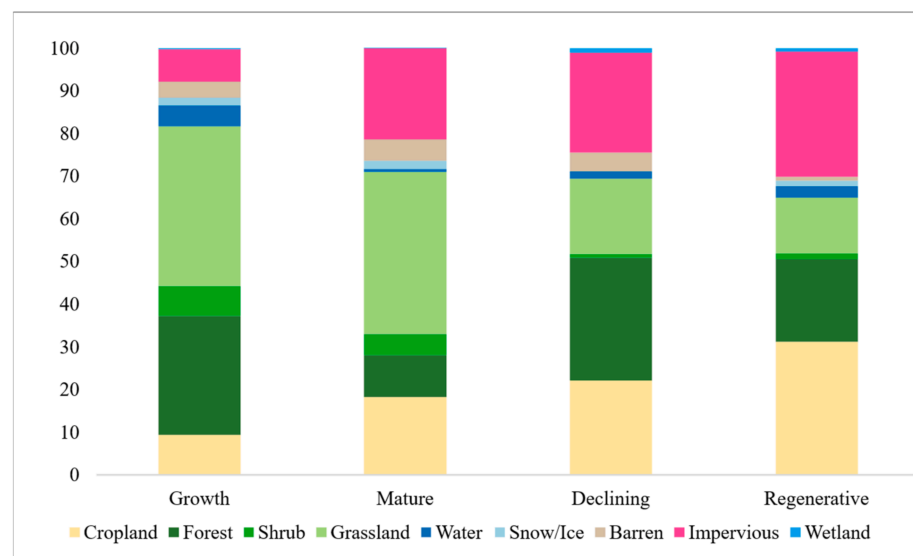


Figure 4. Contribution of land-use change by resource-based city type.

To facilitate comparison among the four development stages, Table 5 provides a concise synthesis of the dominant land-use changes and their main structural characteristics. This qualitative summary is derived from the complete quantitative results presented in Table A1, including the area change, annual dynamic degree, and contribution proportion of each land-use type. Table 5 does not introduce additional calculations but highlights the principal expansion, contraction, and structural features identified from Table A1.

Based on the detailed quantitative results in Table A1, Table 5 summarizes the dominant expansion and contraction patterns across the four development stages. Specifically, mature cities exhibit the largest scale of land-use change. In these cities, impervious surfaces continue to expand, with a dynamic degree of 2.41% and an area increase of

11,925.02 km². Meanwhile, grassland decreases substantially, with a total reduction of 21,255.39 km², indicating that land-use change is characterized mainly by construction land expansion and ecological land contraction. Land-use change in declining cities occurs on a relatively small scale, with changes mainly concentrated among cropland, impervious surfaces, and forest; although impervious surfaces still maintain a relatively high dynamic degree (2.05%), the overall magnitude of change remains limited. Land-use change in growth cities is relatively dispersed, and impervious surfaces expand at the fastest rate, recording a dynamic degree of 3.27%; however, the overall scale of change is relatively limited, and land-use adjustment mainly involves changes in forest, grassland, and cropland. By contrast, regenerative cities exhibit a relatively small overall scale of change, more balanced changes among different land-use types, and a recovery trend in some ecological land, contributing to a relatively stable land-use structure.

Taken together, the comparison across change rate, absolute magnitude, and transition complexity shows that mature cities experienced the largest absolute scale of land-use change, growth cities the fastest expansion of impervious surfaces, regenerative cities the highest comprehensive dynamic degree and a relatively diversified transition structure, and declining cities the weakest overall adjustment.

Table 5. Summary of the dominant land-use changes and structural characteristics of resource-based cities, 2011–2023.

City Type	Main Expanding Land Types	Main Shrinking Land Types	Key Feature
Growth cities	Forest, cropland, and impervious surfaces increased, with impervious surfaces showing the fastest expansion rate	Grassland and shrub decreased markedly	Land-use change was relatively dispersed. Impervious surfaces expanded rapidly, but the overall scale of change was smaller than that in mature cities
Mature cities	Impervious surfaces, cropland, and forest increased substantially	Grassland showed the largest decrease, followed by barren land and shrub	Mature cities had the largest overall scale of land-use change, characterized by construction land expansion and ecological land contraction
Declining cities	Impervious surfaces and cropland increased slightly	Forest and grassland decreased	Land-use change was limited in scale. Impervious surfaces still expanded, but the overall adjustment intensity was weaker
Regenerative cities	Impervious surfaces and forest increased	Cropland and grassland decreased	Construction land expansion and ecological recovery coexisted, and land-use adjustment was more balanced than in mature cities

Note: This table summarizes the principal land-use changes identified from the quantitative results reported in Table A1. “Main expanding land types” and “main shrinking land types” are determined primarily from the direction and magnitude of area change, together with the corresponding dynamic degrees. “Key feature” provides a qualitative synthesis of the overall scale, composition, and direction of land-use adjustment.

3.2. Patterns of Land-Use Carbon Effects in Resource-Based Cities

Structural changes in land use are closely associated with regional carbon emissions. As land-use structure adjusts across development stages, carbon emissions and the carbon source–sink structure also change correspondingly.

3.2.1. Evolution of Net Land-Use Carbon Effects

From 2011 to 2023, net land-use carbon effects in resource-based cities exhibited stage-specific evolutionary characteristics (Figure 5). Differences among city types remained relatively stable across all time points, with mature cities exhibiting the highest net land-use carbon effects, substantially exceeding those of the other city types. Regenerative cities

ranked second, whereas growth and declining cities exhibited relatively low and similar levels of net land-use carbon effects.

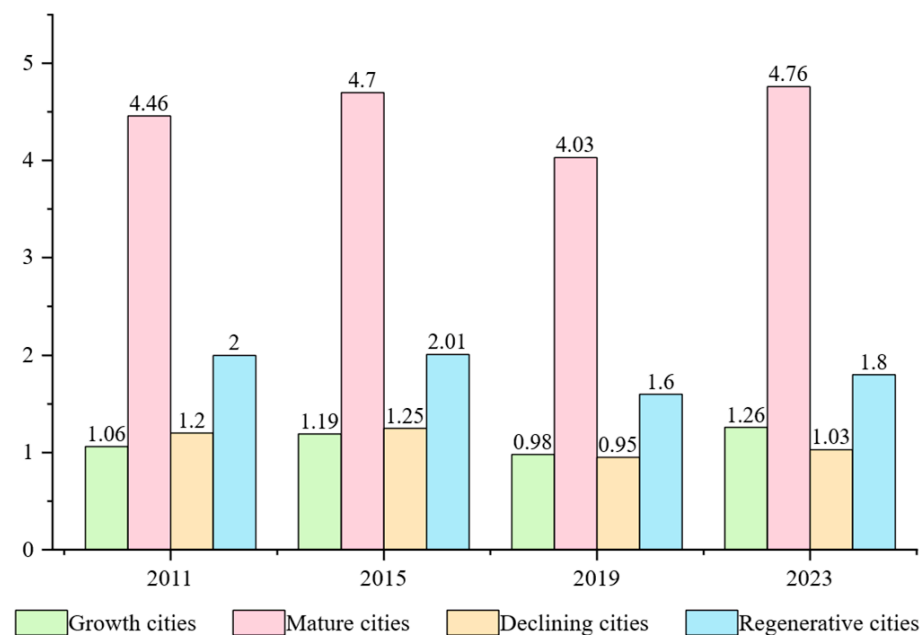


Figure 5. Changes in annual net land-use carbon effects by resource-based city type from 2011 to 2023. Positive values indicate net carbon-source effects, whereas negative values indicate net carbon-sink effects. Unit: 10^8 t C yr^{-1} .

In temporal terms, net land-use carbon effects generally exhibited a temporal pattern of “increase, decrease, rebound” from 2011 to 2023. Specifically, a marked decline occurred during 2015–2019, followed by a rebound during 2019–2023. The analysis is based mainly on land-use and carbon-effect data and does not incorporate policy variables for quantitative identification; therefore, the possible drivers of these stage-specific changes are discussed cautiously as associations rather than causal effects. In terms of variation characteristics across city types, mature cities maintained relatively high levels of net land-use carbon effects with comparatively small fluctuations, demonstrating strong stability. Growth and declining cities showed relatively lower levels of net land-use carbon effects, but both exhibited moderate temporal fluctuations. Regenerative cities displayed larger fluctuations, with more pronounced stage-specific turning points. Overall, the development stage is associated with differences in both the magnitude and temporal stability of net land-use carbon effects: mature cities remain at high and relatively stable levels, regenerative cities show greater fluctuations, and growth and declining cities remain at comparatively lower levels.

3.2.2. Differences in Carbon Source–Sink Structure

Figure 6 presents the carbon source–sink structure of resource-based cities at different development stages in 2011, 2015, 2019, and 2023. Figure 6a shows the carbon-source effects associated with cropland and energy-related emissions represented by impervious surfaces. Figure 6b shows the carbon-sink effects associated with forest, shrub, grassland, water, snow/ice, barren land, and wetland. Positive values indicate carbon emissions, whereas negative values indicate carbon sequestration.

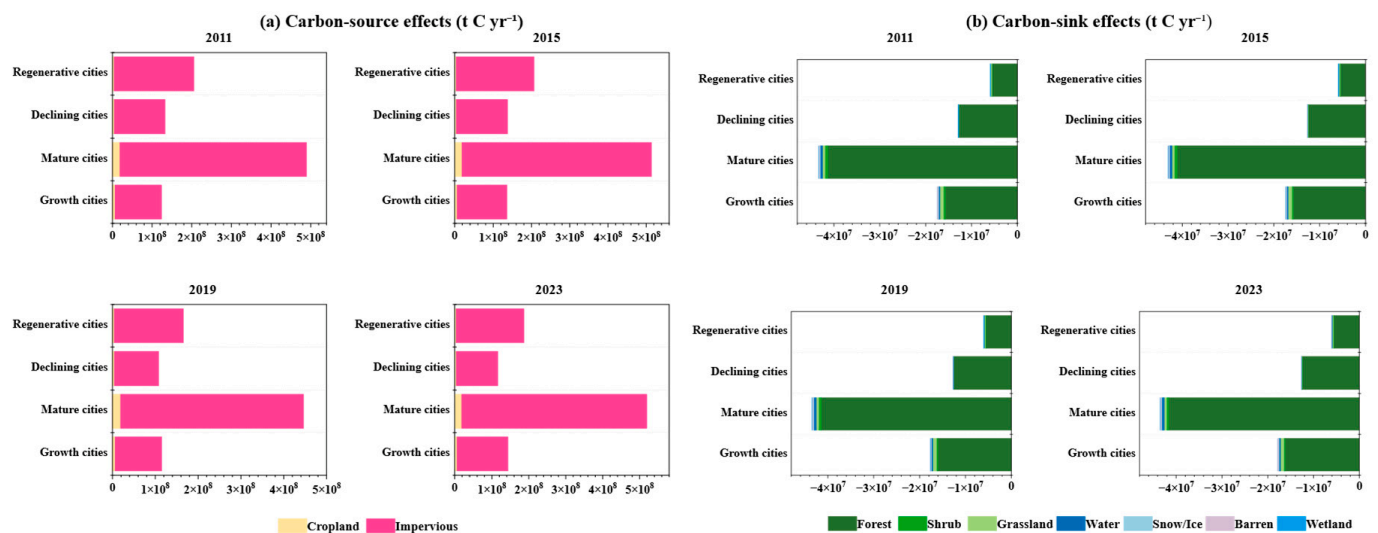


Figure 6. Carbon source–sink structure of resource-based cities by development stage in 2011, 2015, 2019, and 2023. (a) Carbon-source effects associated with cropland and energy-related emissions represented by impervious surfaces and (b) carbon-sink effects associated with forest, shrub, grassland, water, snow/ice, barren land, and wetland. Positive values indicate carbon emissions, whereas negative values indicate carbon sequestration. Unit: t C yr^{-1} .

The results show that energy-related emissions represented by impervious surfaces constitute the dominant carbon-source component across all development stages, while cropland contributes only a small proportion. Mature cities exhibit the highest carbon-source effects throughout the study period, followed by regenerative cities, whereas growth and declining cities remain at relatively lower levels. In terms of carbon sinks, forests are the dominant land-use type, while the contributions of shrub, grassland, water, snow/ice, barren land, and wetland are comparatively small. Mature cities have the largest absolute carbon-sink effects, followed by growth cities, whereas declining and regenerative cities exhibit relatively smaller carbon-sink effects. Overall, carbon-source effects are mainly associated with energy-consuming activities concentrated on impervious surfaces, while carbon-sink effects are primarily determined by the forest.

3.2.3. Spatial Patterns of Net Land-Use Carbon Effects

To further examine the spatial differentiation of net land-use carbon effects, we map their distribution across four development-stage types of resource-based cities in 2011 and 2023 (Figure 7). The corresponding spatial distributions for 2015 and 2019 are provided in Figure A1 in Appendix A. Figures 7 and A1 use the same classification thresholds and color scale, allowing the spatial patterns of different city types and years to be compared directly. Values below zero indicate net carbon-sink effects, whereas positive values indicate net carbon-source effects.

As shown in Figures 7 and A1, net land-use carbon effects show clear spatial heterogeneity across different development stages. Mature cities have the most pronounced high-value clusters, mainly in traditional resource-dependent and industrial regions such as northeast China, north China, and parts of central China. This pattern remains relatively stable from 2011 to 2023. Growth cities show a more dispersed distribution, with high-value areas mainly located in some northern and western resource-exploiting regions, and their spatial pattern varies more markedly across years.

Declining cities generally remain at low-to-medium levels, with weak spatial agglomeration and only a few local high-value areas. Regenerative cities also show a scattered pattern, and most of them remain at low or moderate levels. This indicates that indus-

trial contraction, ecological restoration, and weakening resource dependence may reduce carbon-source pressure to some extent, although construction land expansion and residual industrial activities still affect some cities. Overall, high net land-use carbon effects are closely related to resource exploitation intensity, construction land expansion, and industrial agglomeration, while ecological land and lower development intensity tend to moderate net land-use carbon effects.

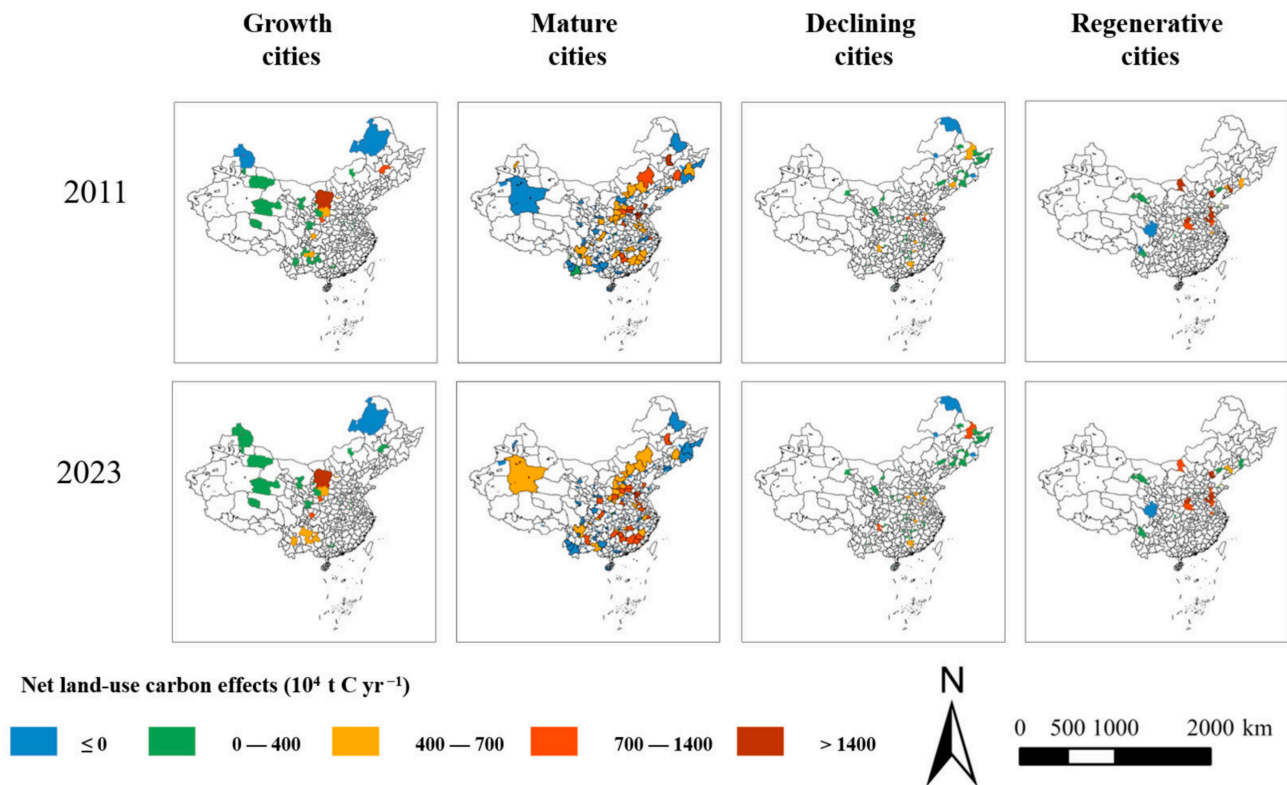


Figure 7. Spatial distribution of annual net land-use carbon effects in growth, mature, declining, and regenerative resource-based cities in 2011 and 2023. The same classification thresholds and color scale are used in all panels. Positive values indicate net carbon-source effects, whereas negative values indicate net carbon-sink effects. Unit: 10^4 t C yr^{-1} .

3.3. Driving Factors of Land-Use Carbon Effects in Resource-Based Cities

3.3.1. GeoDetector Results

Table 6 shows the single-factor detection results for the spatial differentiation of net land-use carbon effects from 2011 to 2023. Overall, the driving factors show substantial differences in explanatory strength. Among them, population size maintains relatively high explanatory strength, as its q value increased from 0.50 in 2011 to 0.66 in 2023, indicating a strong association between population size and the spatial distribution of net land-use carbon effects [49,50]. Energy intensity ranks second in explanatory power, with its q value fluctuating between 0.24 and 0.29 and showing a slight decline, suggesting that energy intensity is associated, to some extent, with the spatial differentiation of net land-use carbon effects [50,51]. However, its overall effect remains relatively stable. By contrast, the explanatory power of economic development level, measured by total GDP, is relatively low and declines from 0.14 in 2011 to 0.05 in 2023. This result indicates that the overall scale of regional economic activity alone has limited explanatory power for the spatial differentiation of net land-use carbon effects in resource-based cities. For land-use structural variables, the proportions of impervious surface and ecological land show relatively weak explanatory power under single-factor detection, with no clear temporal trend. Their effects

on the spatial differentiation of net land-use carbon effects may therefore be more evident when interacting with factors such as population, economic development, and energy use.

Table 6. Results of single-factor detection for resource-based cities.

Factor	2011	2015	2019	2023
Population size	0.50	0.56	0.63	0.66
Economic development level (GDP)	0.14	0.10	0.07	0.05
Energy intensity	0.28	0.29	0.25	0.24
Proportion of impervious surfaces	0.15	0.14	0.11	0.09
Proportion of ecological land	0.09	0.13	0.11	0.08

The interaction detection results in Figure 8 further show that combinations of factors explain the spatial differentiation of net land-use carbon effects better than single factors. Most factor combinations exhibit bivariate or nonlinear enhancement, consistent with the way interaction effects are interpreted in GeoDetector. Among these combinations, the interaction terms between population size and economic development level measured by total GDP, as well as those between population size and energy intensity, show relatively high *q* values in all years, indicating strong synergistic relationships between population size and other variables under different socioeconomic conditions. In 2019, all interaction terms had higher *q* values than the corresponding single factors, suggesting that the association among multiple factors strengthened during this stage. Notably, although the economic development level measured by total GDP shows relatively low explanatory power under single-factor detection, its interaction with population size exhibits relatively high explanatory power. This suggests that the overall scale of regional economic activity may influence the spatial pattern of net land-use carbon effects more strongly when combined with population agglomeration than when considered independently.

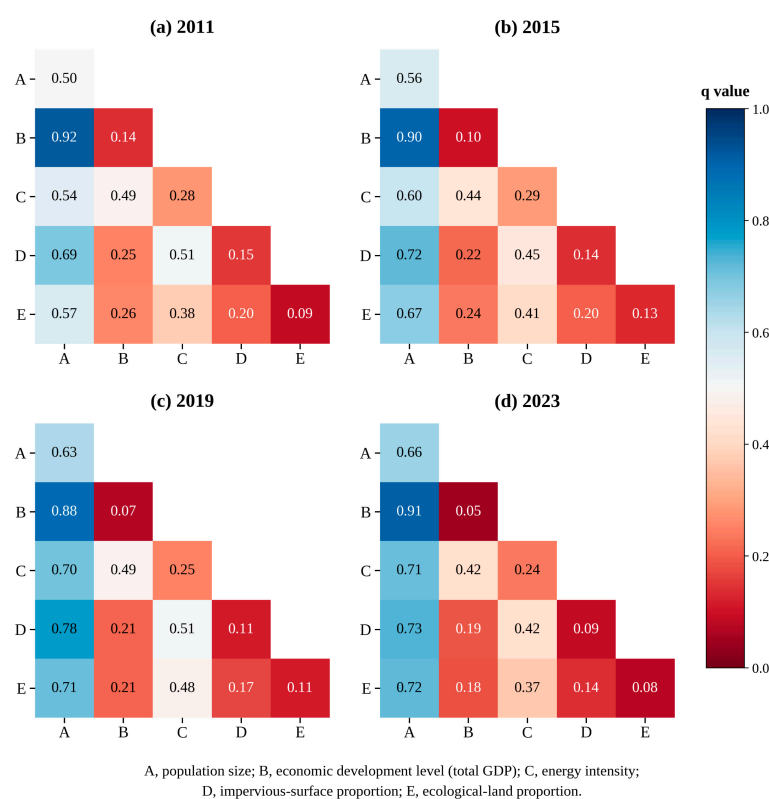


Figure 8. Interaction detection results for driving factors of net land-use carbon effects in resource-based cities.

Overall, spatial differentiation of net land-use carbon effects reflects the combined influence of multiple factors. Population size consistently remains a key factor shaping spatial patterns of net land-use carbon effects. In contrast, land-use structural variables, despite their limited individual explanatory power, show clear enhancement during interactions with socioeconomic factors, indicating that their influence on the spatial differentiation of net land-use carbon effects is strongly coupled and indirect.

3.3.2. Differences in Driving-Factor Patterns Across City Types

Figure 9 presents the interaction characteristics of factors influencing net land-use carbon effects. Overall, clear differences are observed across development stages in the combinations of driving factors and their interaction effects.

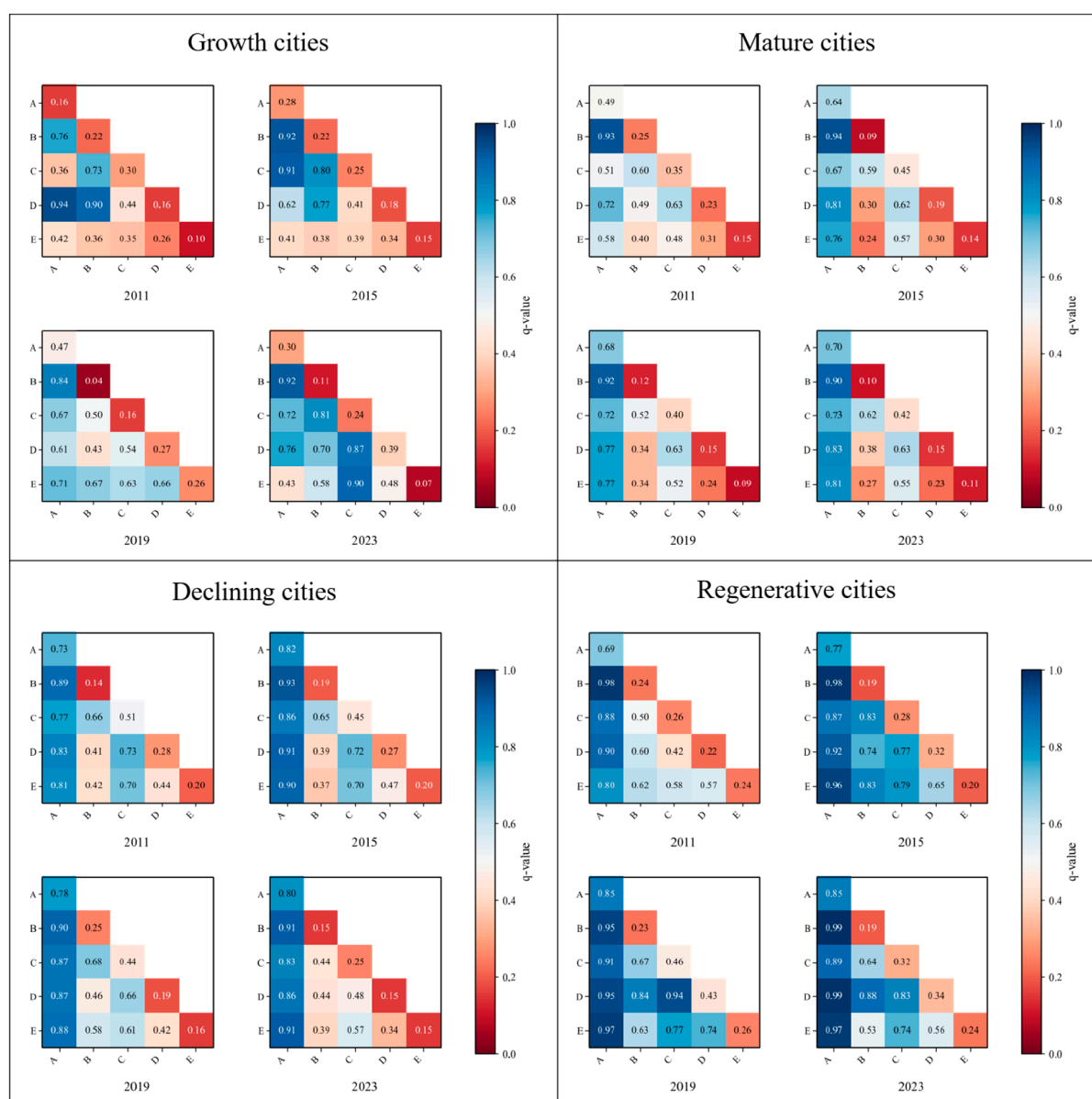


Figure 9. Interaction effects of driving factors on net land-use carbon effects by resource-based city type. The labels A–E are consistent with those in Figure 8.

In regenerative cities, population size shows relatively high single-factor explanatory power. In growth cities, population-related interactions, rather than population size alone, exhibit stronger explanatory power. In particular, the interaction between population

size and economic development level shows a strong enhancement effect, indicating that their joint spatial stratification explains more variation in net land-use carbon effects than either factor alone. In mature cities, factors related to energy intensity exhibit relatively strong explanatory power. The interaction between population size and energy intensity remains relatively high across all study years, indicating that these two factors jointly contribute to the spatial differentiation of net land-use carbon effects. In declining cities, population-related interactions maintain consistently high explanatory power across the study years, although several interactions involving energy intensity and land-use variables show moderate temporal variation.

Overall, energy intensity exhibits relatively high explanatory power across all city types, particularly in mature and declining cities. This indicates that energy intensity is closely associated with the spatial differentiation of land-use carbon effects. Different city types, therefore, show distinct interaction profiles: population-related interactions are more prominent in growth and regenerative cities, whereas energy-intensity-related interactions are more important in mature and declining cities.

4. Discussion

The results indicate that land-use transition in resource-based cities is not merely a process of construction land expansion. Rather, it exhibits pronounced stage-specific differences as resource-exploitation intensity, industrial evolution trajectories, and ecological restoration processes change over time. Growth and mature cities generally show pronounced construction land expansion, indicating that resource exploitation and industrial agglomeration remain important forces driving land-use change. Declining cities exhibit relatively weak overall land-use adjustment, accompanied by continued but limited expansion of impervious surfaces and contraction of several ecological land types. These patterns may be associated with resource depletion and industrial restructuring; however, population outflow and industrial contraction were not directly examined here. Regenerative cities, by contrast, display more evident functional restructuring, shaped by the coexistence of optimization of existing impervious surface land and ecological land recovery, indicating that industrial transformation and ecological restoration are becoming increasingly important and may be contributing to these land-use changes. These findings indicate that development-stage differences are associated with differences in the evolutionary direction of land-use structure and further shape the observed patterns of net land-use carbon effects by altering the spatial configuration of construction and ecological space. There is a clear stage-specific relationship between land-use transition and net land-use carbon effects across city types, indicating that changes in land-use carbon effects in such cities are not simply the result of increases or decreases in emission scale, but rather a composite outcome of land-use structural adjustment, ecological space restoration, and development stage differences.

From a temporal perspective, net land-use carbon effects generally followed a stage-specific pattern of increase, decrease, and rebound during 2011–2023. To some extent, this nonlinear process reflects the alternating effects of economic growth, structural adjustment, and spatial restructuring across city stages. The rise in net land-use carbon effects during the early stage suggests that resource exploitation and construction expansion were still reinforcing carbon-source effects. The mid-period decline may be associated with structural adjustment, slower growth, and ecological restoration in some regions, and strengthened environmental regulation in energy-intensive industries [52]. The subsequent rebound suggests that net land-use carbon effects still exhibit considerable inertia. Spatially, high-value areas are mainly found in regions with intensive resource exploitation and a strong industrial base. By contrast, low-value areas are more often distributed in regions subject

to stronger ecological constraints or experiencing faster ecological restoration, thereby exhibiting marked spatial differentiation. Overall, net land-use carbon effects are influenced not only by development-stage differences but also by regional resource endowments, industrial foundations, and ecological governance conditions. Therefore, analyzing land-use carbon effects across city types helps move beyond a uniform framework that treats resource-based cities merely as general industrial carbon emitters and enables a more accurate identification of stage-specific priorities for low-carbon transition.

Relative to previous research, the proposed framework incorporates cities at different development stages into a unified national-level analysis and systematically compares land-use transitions and associated carbon effects, thereby broadening the scope of land-use carbon research. Net land-use carbon effects are also analyzed through the carbon source–sink structure, rather than considering only total emissions, thereby offering a fuller understanding of the relationship between land-use change and the carbon cycle. These findings are broadly consistent with previous studies linking resource dependence, land-resource allocation, and industrial restructuring to land-use and carbon outcomes in resource-based cities [18,23,24,30]. However, unlike studies that focus mainly on carbon emissions or land-use efficiency, our results show that lower carbon-source effects in declining cities do not necessarily indicate an improved carbon source–sink structure, while ecological recovery in regenerative cities may coexist with continued positive net land-use carbon effects. The interaction results further suggest that land-use structure affects carbon outcomes jointly with population size and energy intensity rather than independently. These findings extend the literature by highlighting the combined importance of development stage and carbon source–sink composition. As noted by Grassi et al. [53], differences in accounting boundaries and conventions may lead to discrepancies among land-sector carbon estimates; accordingly, the results should be interpreted as comparative estimates of land-use carbon effects rather than as a complete urban greenhouse-gas inventory.

5. Conclusions and Policy Implications

5.1. Conclusions

Based on land-use and energy-consumption data for Chinese resource-based cities from 2011 to 2023, the results show that land-use transitions and their land-use carbon consequences are stage-dependent rather than uniform across cities. Growth and mature cities are characterized mainly by construction land expansion; declining cities by relatively weak overall land-use adjustment, accompanied by continued but limited expansion of impervious surfaces and contraction of several ecological land types; and regenerative cities by the coexistence of construction land adjustment and ecological restoration. Correspondingly, net land-use carbon effects exhibit a nonlinear pattern of increase, decline, and rebound, together with marked spatial heterogeneity. Population size shows the strongest independent explanatory power, while its interactions with economic development, energy intensity, and land-use structure further strengthen the spatial differentiation of net land-use carbon effects.

The principal scientific contribution lies in integrating an official development-stage classification, the assessment of carbon-source effects, carbon-sink effects, and net land-use carbon effects, and GeoDetector interaction analysis within a unified city-level framework. This framework demonstrates that similar land-use transitions may be associated with different land-use carbon effects depending on resource dependence, industrial structure, population agglomeration, and ecological restoration processes. Accordingly, the framework extends previous land-use carbon research from a general comparison of cities toward a stage-specific explanation of the relationships among urban transition, land-use restructuring, and the carbon source–sink structure.

5.2. Policy Implications

Based on the analytical conclusions presented above, differentiated policy measures are proposed for resource-based cities at different development stages. Growth cities should give priority to controlling unplanned growth in impervious surfaces, improving land-use intensity, and guiding energy-intensive industries toward low-carbon transformation to alleviate land-use-related carbon-source pressure caused by rapid expansion. Mature cities should shift the regulatory focus from incremental expansion to the optimization of existing stock, improve energy-use efficiency through technological upgrading, and promote a transition toward cleaner energy sources, thereby reducing the high-carbon lock-in effect associated with extensive impervious surfaces and energy-intensive activities. Declining cities should promote a shift in urban development from outward expansion to inward improvement, revitalize existing impervious surfaces, and strengthen mining-area restoration and ecological governance to facilitate the conversion of inefficient land into ecological land with carbon-sequestration functions. Regenerative cities, based on consolidating existing transformation achievements, should continue to advance industrial upgrading toward higher-end and lower-carbon development, while strengthening ecological-space protection and restoration to further enhance ecosystem carbon-sink functions. In general, the evolution of net land-use carbon effects is closely related to the development stage, and future efforts should coordinate land-use transition, ecological protection, and economic development to build a low-carbon development pathway that combines differentiation with stage-specific governance.

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Data Availability Statement: The land-cover data used in the analysis were obtained from Version 1.0.4 of the 30 m annual China Land Cover Dataset developed by Yang and Huang, as cited in [40]. The methodological framework, classification system, and accuracy assessment of the dataset are described in [10]. Socioeconomic data were collected from the China Statistical Yearbook, the China City Statistical Yearbook, and relevant provincial and municipal statistical yearbooks. Administrative boundary data were obtained from official geospatial data sources. The processed data supporting the reported findings are available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

CLCD	China Land Cover Dataset
GDP	Gross domestic product
IPCC	Intergovernmental Panel on Climate Change
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology

Appendix A

Table A1 presents the complete quantitative results underlying the summary in Table 5. It reports the area change, annual dynamic degree, and contribution proportion of each land-use type for growth, mature, declining, and regenerative cities. Positive area changes indicate expansion, whereas negative values indicate contraction. These quantitative results were used to identify the dominant land-use changes and structural characteristics summarized in Table 5.

Table A1. Detailed land-use area changes, annual dynamic degrees, and contribution proportions of resource-based cities by development stage, 2011–2023.

City Type	Land-Use Type	Δ area (km ²)	Dynamic Degree (%)	Proportion (%)
Growth cities	Cropland	2905.47	0.16	9.34
	Forest	8664.85	0.27	27.85
	Shrub	−2193.37	−2.82	7.05
	Grassland	−11,628.72	−0.26	37.38
	Water	1542.39	1.21	4.96
	Snow/Ice	−545.62	−1.08	1.75
	Barren	−1188.00	−0.03	3.82
	Impervious surfaces	2371.72	3.27	7.62
	Wetland	71.26	2.09	0.23
Mature cities	Cropland	10,185.39	0.19	18.19
	Forest	5514.56	0.06	9.85
	Shrub	−2762.71	−2.11	4.93
	Grassland	−21,255.39	−0.67	37.95
	Water	378.52	0.16	0.68
	Snow/Ice	−1138.59	−1.40	2.03
	Barren	−2801.06	−0.06	5.00
	Impervious surfaces	11,925.02	2.41	21.29
	Wetland	−45.73	−0.74	0.08
Declining cities	Cropland	2531.31	0.19	22.15
	Forest	−3284.88	−0.12	28.75
	Shrub	−93.24	−2.33	0.82
	Grassland	−2019.12	−0.60	17.66
	Water	−191.61	−0.48	1.68
	Snow/Ice	−0.02	−8.33	0.00
	Barren	508.16	0.33	4.45
	Impervious surfaces	2673.52	2.05	23.40
	Wetland	−124.13	−3.26	1.09
Regenerative cities	Cropland	−3984.45	−0.34	31.20
	Forest	2465.57	0.22	19.31
	Shrub	169.89	0.83	1.33
	Grassland	−1670.01	−0.14	13.08
	Water	−349.14	−0.60	2.73
	Snow/Ice	−159.57	−1.84	1.25
	Barren	−119.53	−0.08	0.94
	Impervious surfaces	3749.28	1.71	29.36
	Wetland	−102.04	−3.39	0.80

Note: Δ area denotes the net area change between 2011 and 2023. Dynamic degree denotes the average annual rate of change in each land-use type. Proportion denotes the share of the absolute area change of each land-use type in the total absolute area change of the corresponding city group.

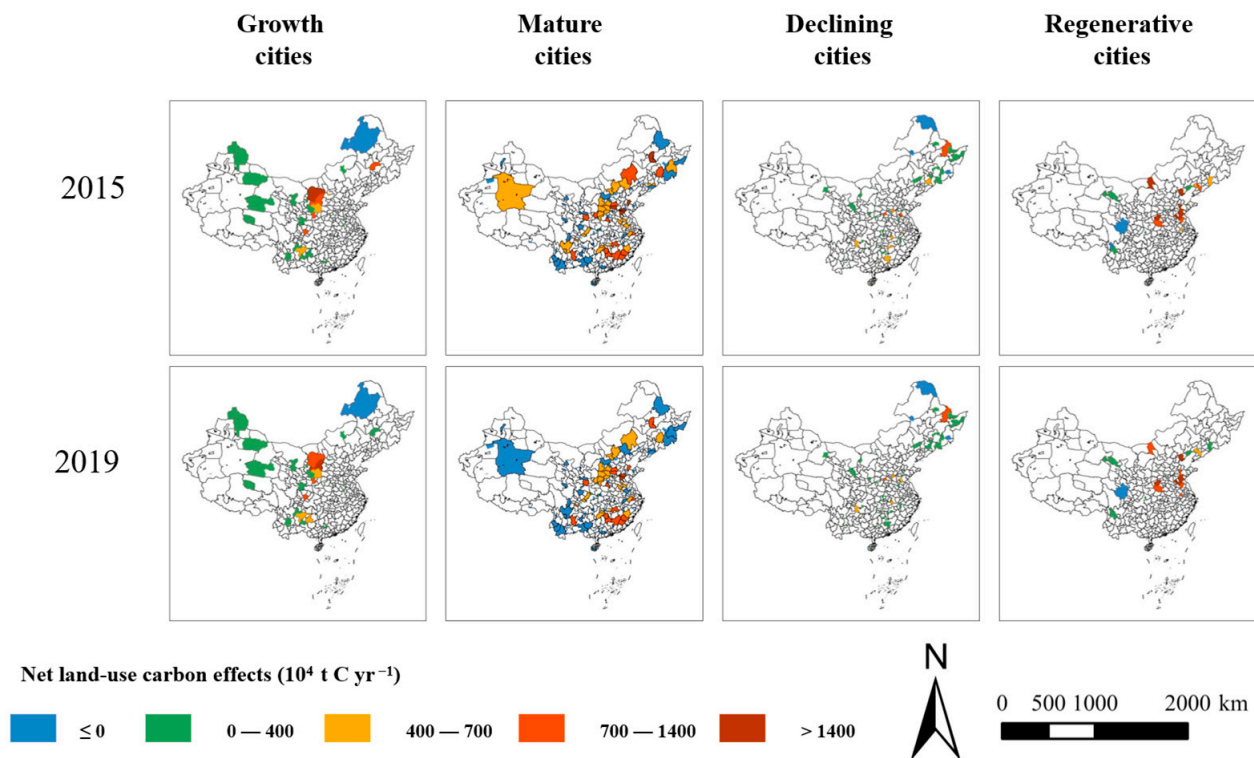


Figure A1. Spatial distribution of annual net land-use carbon effects in growth, mature, declining, and regenerative resource-based cities in 2015 and 2019. The same classification thresholds and color scale as those in Figure 7 are used. Positive values indicate net carbon-source effects, whereas negative values indicate net carbon-sink effects. Unit: 10^4 t C yr^{-1} .

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