



A Study on the Spatiotemporal Characteristics, Decoupling Effects, and Influencing Factors of Carbon Emissions in the Five Northwestern Provinces

Jiahui Yu*

Northwest Normal University, Lanzhou 730070, China
*xbsdyjh0923@qq.com

Abstract. As a major energy-rich region and heavy industrial base in China, the five northwestern provinces shoulder critical responsibilities in achieving the nation's carbon peaking and carbon neutrality goals. Due to their resource-based industrial structure, these provinces exhibit a high-carbon lock-in, facing significant pressure to reduce emissions. Based on panel data from prefecture-level cities in this region from 2011 to 2023, this study systematically analyzes the spatiotemporal patterns, decoupling status, and influencing factors of carbon emissions. First, the carbon emission coefficient method is employed to calculate emissions and examine regional trends. Building on this foundation, the Tapio decoupling model is applied to investigate the relationship between carbon emissions and economic growth. Subsequently, an extended STIRPAT model combined with ridge regression is used to empirically test influencing factors, leading to regionally differentiated emission reduction recommendations. The findings reveal an overall upward trend in carbon emissions across the five northwestern provinces, accompanied by significant regional disparities. Resource-rich areas and heavy industrial bases face particularly acute carbon emission pressures. The relationship between carbon emissions and economic growth exhibits distinct dynamic evolution characteristics. Key drivers of carbon emission growth in these provinces include total energy consumption, the proportion of secondary industry, population density, and per capita GDP. Based on this analysis, it is recommended that the five northwestern provinces accelerate energy efficiency improvements, promote green industrial restructuring, optimize population spatial distribution, implement tailored policies for cities at different decoupling stages, and establish precise regional emission reduction pathways.

Keywords: Carbon emissions, Tapio decoupling model, STIRPAT model, influencing factors, five northwestern provinces

1 Introduction

In recent years, China has explicitly set strategic goals for carbon peaking and carbon neutrality. As a typical resource-based region, the five northwestern provinces face severe pressure to reduce emissions. Historically, leveraging its resource endowments, the Northwest has developed an industrial structure dominated by energy extraction,

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heavy chemical industries, and non-ferrous metal smelting. This structure is characterized by a heavy industrial focus and coal-intensive energy consumption. While high-energy-consuming and high-emission industries have supported regional economic growth, they have also incurred substantial resource and environmental costs.

Carbon accounting forms the foundation for achieving dual carbon goals, with current research deepening from macro-level accounting to specific industries and process stages. Jin Kun et al. (2025)^[1] employed multi-source data fusion and artificial intelligence techniques to develop statistical measurement and accounting methods for power system carbon emissions. Huang Miao et al. (2024)^[2] utilized a three-life function evaluation and spatial carbon emission coefficient measurement model to conduct strategic simulations and pattern optimization of county-level three-life spatial carbon emission coefficients in Hunan Province. Huang Meizhong et al. (2022)^[3] employed a top-down/bottom-up integration approach combined with the Tapio decoupling model to measure and analyze spatial differentiation of tourism carbon emission decoupling effects in the Yangtze River Delta urban cluster.

To identify carbon emission drivers, studies often integrate extended models with decomposition methods. Zeng Wei et al. (2023)^[4] analyzed Hubei's carbon emissions using the STIRPAT model, indicating that technological systems and industrial restructuring can drive carbon peaking. Li Jian et al. (2025)^[5] decomposed transportation carbon emissions in the Beijing-Tianjin-Hebei region using LMDI, identifying per capita GDP as the primary driver. Zhang Jiangyan (2024)^[6] combined STIRPAT with LMDI to establish quantitative relationships between factors and decoupling indices, enhancing analytical interpretability. Qi Yu et al. (2024)^[7] decomposed logistics sector carbon emissions using an extended Kaya equation and LMDI, indicating that low-carbon technologies are the primary suppressing factor, while industry revenue and population size exert promoting effects. Wang Jiawei et al. (2025)^[8] conducted spatiotemporal evolution analysis and driver decomposition of carbon emission efficiency in the Beijing-Tianjin-Hebei region using nighttime light data and the Super-EBM model.

Carbon peak predictions often employ scenario simulations to evaluate policy pathways. Xu Weijun et al. (2024)^[9] combined STIRPAT and Monte Carlo simulations to model carbon pathways for the Greater Bay Area. Su Jianjun et al. (2025)^[10] employed a GM(1,1) model to forecast carbon emissions from western China's tourism sector, indicating continued growth over the next decade with tourism transportation as the primary emitting sector. These studies reveal the critical impact of policy interventions on peak timing through multi-scenario analysis.

2 Current Status of Economic Development and Carbon Emissions in Urban Agglomerations of the Five Northwestern Provinces

2.1 Analysis of Economic Development Evolution

Spatiotemporal Evolution of Per Capita GDP.

Based on per capita GDP data from provincial capitals and prefecture-level cities

across the five northwestern provinces, the overall per capita GDP of cities in the north-west region showed a significant upward trend from 2011 to 2023. This trend objectively reflects the sustained economic growth in the region over more than a decade, with major cities within each province achieving leapfrog improvements in economic levels(Fig. 1).

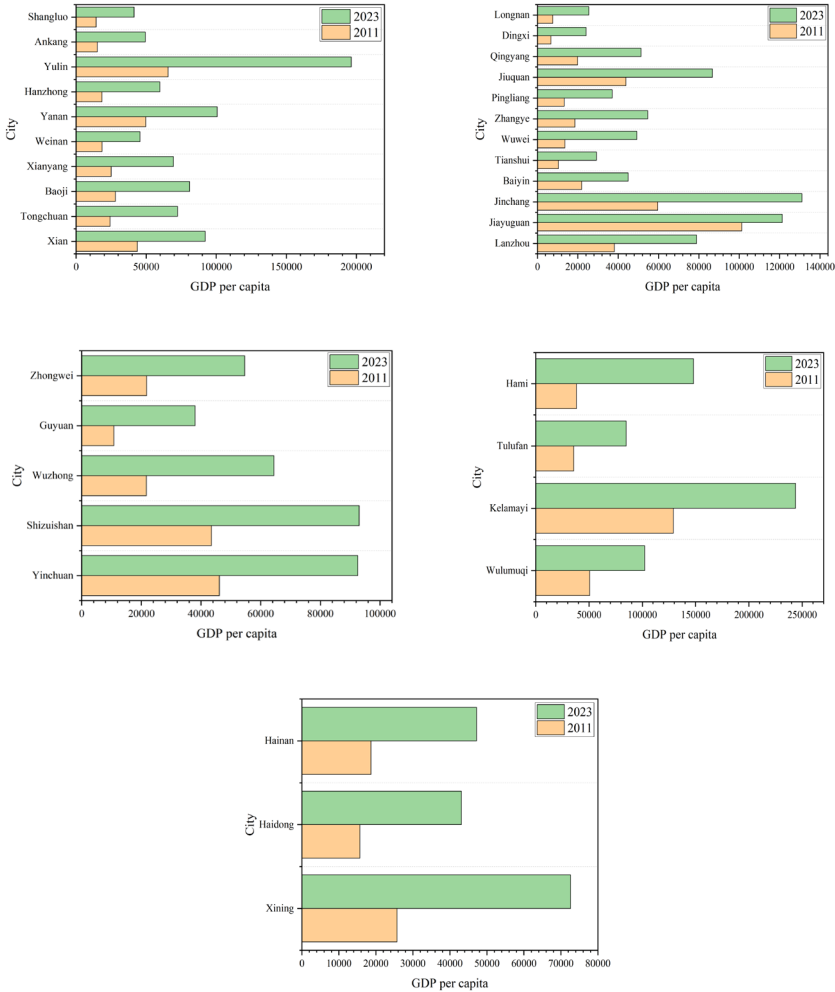


Fig. 1. Per Capita GDP of Prefecture-Level Cities in the Five Northwestern Provinces

In terms of growth rate, Yulin City in Shaanxi Province stands out remarkably. Its per capita GDP surged from 61,800 yuan in 2011 to 196,300 yuan in 2023, representing a growth multiple of approximately 3.0 times, making it the city with the highest growth rate in the Northwest. In contrast, Tongchuan City, also in Shaanxi Province, saw its per

capita GDP rise from 24,300 yuan in 2011 to 72,400 yuan in 2023. Both its absolute increase and growth rate were among the lowest in the province, making it the city with the smallest relative growth.

Notably, some cities with low baseline figures demonstrated robust growth potential. Hainan Tibetan Autonomous Prefecture in Qinghai Province, with a per capita GDP below ¥18,700 in 2011 and ranking near the bottom in Northwest China, reached ¥47,200 by 2023. Its growth multiplier ranked among the highest in the region, achieving leapfrog development that defied expectations of continued low economic growth. Longnan City in Gansu Province exhibits similar characteristics, with per capita GDP rising from ¥7,600 in 2011 to ¥25,500 in 2023. Its growth multiplier is equally significant, and its development momentum far exceeds that of many cities within the province with stronger economic foundations.

Spatial-Temporal Population Shifts.

Based on permanent resident population data from the five provincial capitals in Northwest China, the region's major cities—represented by these five capitals—saw comprehensive population growth from 2011 to 2023. Xi'an leads in both total population and growth increment, while Yinchuan exhibits the most remarkable growth rate, representing distinct development models and pathways for provincial capitals. This trend of population concentration in provincial capitals reinforces the dominant role of core cities in regional economic development. It also reflects the overall pattern in the urbanization process of Northwest China, where the primacy of provincial capitals continues to rise and the population agglomeration effect steadily intensifies (Fig. 2).

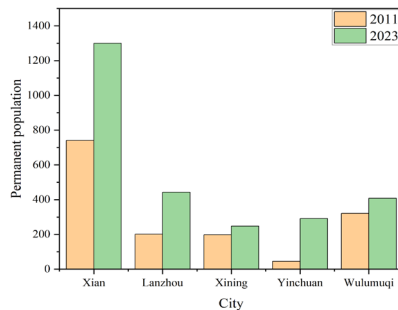


Fig. 2. Population of Provincial Capitals in the Five Northwest Provinces

2.2 Analysis of Current Carbon Emissions

Overall Scale and Temporal Variations in Carbon Emissions.

Overall, carbon emissions across cities in Shaanxi Province generally show an upward trend, with Yulin City experiencing particularly significant growth. Most cities in Gansu Province also exhibit increasing emissions, though some like Tianshui City show relatively moderate growth. Qinghai's cities have maintained stable overall growth in

carbon emissions, with the provincial capital Xining showing more pronounced increases. Ningxia Hui Autonomous Region's cities all exhibit upward trends, with the capital Yinchuan demonstrating the most prominent growth. Cities across Xinjiang Uygur Autonomous Region generally show rising emissions, with Hami experiencing the most significant increase (Fig. 3).

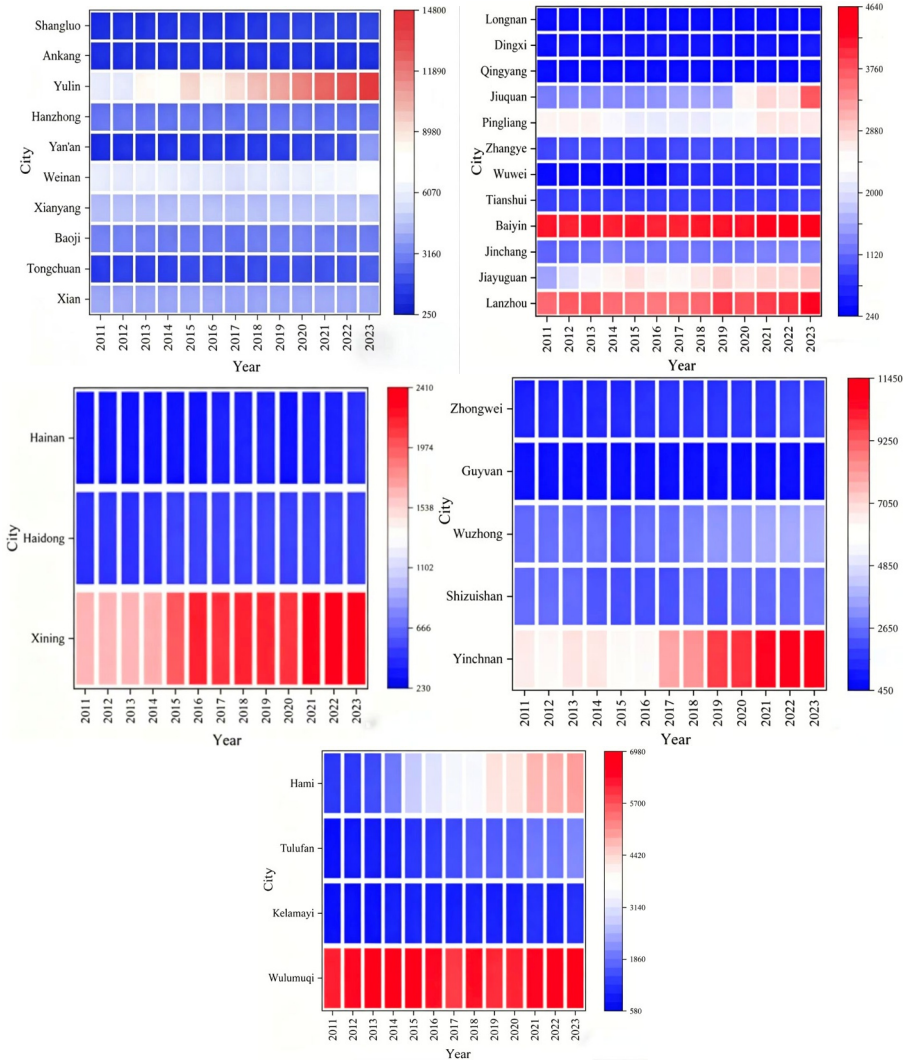


Fig. 3. Carbon Emissions Scale in the Five Northwestern Provinces

Specifically, Yulin City in Shaanxi Province recorded the largest increase in carbon emissions, rising by approximately 85.13 million tons. Jiuquan City recorded the largest carbon emissions increase, rising by approximately 26.22 million tons. Xining saw the largest increase in carbon emissions, rising by approximately 7.44 million tons.

Yinchuan recorded the highest emissions growth, climbing by roughly 50.77 million tons. Zhongwei experienced the swiftest expansion, adding about 8.34 million tons—an increase of approximately 87%.Hami City recorded the largest increase in carbon emissions, rising by approximately 37.57 million tons.Some cities experienced smaller or slower carbon emission growth, potentially due to the upgrading and restructuring of traditional industries. For example, Tianshui City, as an old industrial base, has gradually promoted industrial transformation in recent years. The closure or relocation of some high-energy-consuming enterprises has slowed the growth of carbon emissions.Regions with higher agricultural proportions, such as Dingxi City and Longnan City, exhibit relatively single economic structures and slower industrialization processes. Their low baseline energy consumption limits the potential for carbon emissions growth. Furthermore, the promotion and application of clean energy have also curbed emissions growth to some extent. Some areas have optimized their energy structures by developing wind and solar power projects.

Overall, regions with faster carbon emission growth are predominantly concentrated in resource-rich areas, heavy industrial bases, or rapidly developing economic zones. These locations exhibit robust energy consumption demand and a heavy industrial structure. Conversely, regions with slower or minimal growth often face characteristics such as industrial transformation, a single economic structure, or an early start in clean energy substitution. These regional disparities in carbon emissions reflect differences in local economic development levels, industrial structure features, and energy consumption patterns.

2.3 The Decoupling of Carbon Emission Intensity and Economic Growth

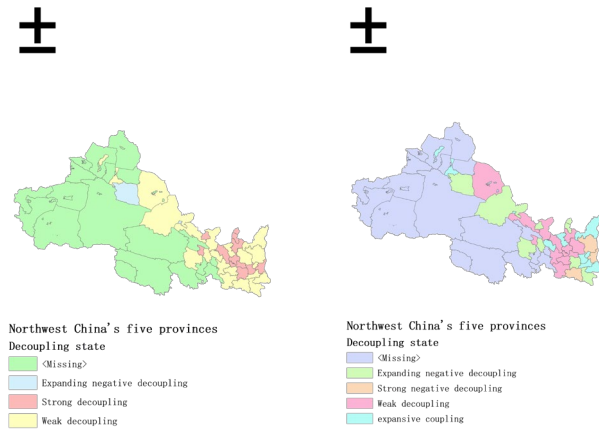


Fig. 4. Decoupling status of carbon emissions from economic growth in the five northwestern provinces

The dynamic shifts in decoupling status across cities primarily stem from underlying factors including industrial structure characteristics, resource development stages, en-

ergy consumption patterns, and macroeconomic environments. Fig. 4 illustrates the decoupling status of each city. A detailed explanation follows.

Shaanxi Province exhibits the most pronounced fluctuations in decoupling status, fundamentally attributable to its internally divided industrial structure. As a national energy and chemical base, Yulin City's economic growth heavily relies on coal mining, thermal power generation, and coal chemical industries—sectors inherently characterized by high energy consumption and emissions. In 2012, Yulin maintained weak decoupling, benefiting from the initial effectiveness of energy efficiency enhancement policies. By 2023, it exhibited expansive coupling, directly caused by increased energy supply pressures post-pandemic, which spurred renewed expansion of coal chemical projects.

Gansu Province exhibits significant regional divergence in decoupling patterns, rooted in variations in carbon intensity across dominant industries in different cities. Jiayuguan City, dominated by steel smelting—a process characterized by lengthy production cycles, high energy intensity, and relatively lagging technological upgrades—has consistently maintained a state of negative decoupling or strong negative decoupling across the four years, highlighting the formidable challenges of low-carbon transformation for metallurgical industrial cities. Jiuquan City's decoupling status fluctuated from weak to deteriorating, reflecting the tug-of-war between its new energy equipment manufacturing sector and traditional thermal power generation. However, in 2023, negative decoupling expanded again, indicating that the stability of new energy substitution still needs strengthening. Qinghai Province's decoupling fluctuations are closely tied to the progress of clean energy substitution. As the provincial capital, Xining's population and industrial concentration drive sustained energy demand. Its strong decoupling in 2012 stemmed from high hydropower penetration. more illustrative. Initially dominated by traditional agriculture and animal husbandry with a low carbon emissions baseline, it exhibited weak decoupling. In 2023, it reverted to expansionary negative decoupling, potentially linked to short-term emission increases from supporting new energy industries like energy storage and polysilicon projects. This indicates persistent phased carbon emission pressures during clean energy base development.

Ningxia Hui Autonomous Region initially demonstrated strong performance but later showed significant divergence, closely tied to the development pace of the Ningdong Energy and Chemical Industry Base. Shizuishan City, benefiting from an earlier transition of its old industrial base, showed gradual improvement amid fluctuations. Guyuan City and Zhongwei City, with smaller economic scales and more diverse industrial structures, were less directly affected by energy projects, resulting in relatively stable decoupling states.

The complexity of decoupling in Xinjiang Uygur Autonomous Region stems from the overlap of resource development cycles and industrial policy adjustments. Hami City, relying on coal resource development and coal-fired power/coal chemical projects, exhibited weak decoupling in 2012. Later, with energy-saving upgrades and the construction of external transmission channels, it returned to weak decoupling by 2023, demonstrating phased characteristics. Turpan City experienced more pronounced fluctuations, deteriorating from expansion negative decoupling to strong negative decoupling before recovering to strong decoupling. This pattern aligns with the alternating

development cycles of local oil and gas extraction and the photovoltaic industry. Urumqi and Karamay, as the provincial capital and an oil city respectively, possess relatively diversified industrial structures. However, both shifted to expansion coupling in 2023, reflecting a temporary rebound in carbon emissions during the post-pandemic economic recovery driven by the resumption of traditional industries.

3 Carbon Peak Predictions for Urban Agglomerations in the Five Northwestern Provinces

3.1 Introduction to the STIRPAT Model

This study employs the STIRPAT model to empirically analyze factors influencing carbon emissions across the five northwestern provinces. Developed by Dietz and Rosa as an extension of the IPAT model, STIRPAT incorporates regression analysis and random error terms to more accurately capture the nonlinear relationship between environmental impacts and factors such as population, affluence, and technological advancement. It is widely applied in carbon emissions research. The model is expressed as:

$$I = aPbAcTde \tag{1}$$

Taking logarithms of both sides of equation (1) yields a linear form (2):

$$\ln I = a + b \ln P + c \ln A + d \ln T + e \tag{2}$$

where *a* is the model constant term; *b*, *c*, and *d* represent the elasticity coefficients for population size, affluence level, and technological level, respectively, indicating the percentage change in carbon emissions caused by a 1% variation in each factor; *e* is the model error term.

3.2 Indicator Selection and Data Sources

In terms of indicator selection, this study adopts the theoretical framework of the STIRPAT model while comprehensively considering the regional characteristics of the five northwestern provinces and data availability. Explanatory variables were selected that systematically reflect multiple dimensions including population size, economic development, industrial structure, spatial agglomeration, resource utilization, energy consumption, and environmental regulation (Table 1). Total CO₂ emissions serve as the dependent variable.

Table 1. Variable Definitions and Measurements

Variable Type	Dimension	sign	Measurement Method
Y	Carbon Emissions	I	Calculated using the carbon emission factor method
	Population Size	P ₁	Permanent resident population at year-end
	Population Concentration	P ₂	Permanent Residents/Administrative Area
	Economic Development	A	Regional GDP/Permanent Residents

Industrial Structure	IS	Secondary Industry Value Added as a Percentage of GDP
Energy Consumption	EC	Regional Energy Consumption
Resource Utilization	RU	General Solid Waste Comprehensive Utilization Rate
Environmental Regulations	ER	Share of Energy Conservation and Environmental Protection Expenditures in Fiscal Expenditures

In the demographic dimension, total population was selected to reflect the foundational impact of regional population scale on carbon emissions, while population density was chosen to indicate the spatial concentration of human activities. In the economic development dimension, per capita GDP was selected as an indicator of affluence to examine the correlation between economic growth and carbon emissions. In the industrial structure dimension, the share of secondary industry value-added in GDP was selected to reflect the driving role of industrialization in carbon emissions. Given the high proportion of resource-based industries in Northwest China, incorporating this variable helps reveal the structural impact of industrial structure on carbon emissions. In the energy consumption dimension, total energy consumption was chosen as the core explanatory variable, directly measuring the contribution of energy input scale to carbon emissions—a key variable in carbon emission driver studies. In the environmental regulation dimension, the proportion of fiscal expenditure allocated to energy conservation and environmental protection was selected to reflect local governments' investment intensity in environmental protection, thereby examining the actual effectiveness of policy interventions on carbon emissions.

Based on the above indicator selection, the STIRPAT extended model constructed in this study is as follows (3):

$$\ln I = a + \beta_1 \ln P_1 + \beta_2 \ln P_2 + \beta_3 \ln A + \beta_4 \ln IS + \beta_5 \ln EC + \beta_6 \ln RU + \beta_7 \ln ER + e \quad (3)$$

Where *a* is the constant term, β_1 to β_7 represent the elasticity coefficients of each explanatory variable, indicating the percentage change in carbon emissions caused by a 1% change in each factor, and *e* is the random error term.

The primary data sources include provincial statistical yearbooks from 2011 to 2023, the China Urban Statistical Yearbook, the China Energy Statistical Yearbook, and the China Environmental Statistical Yearbook. For missing data in a few specific years, linear interpolation was employed to ensure the continuity and integrity of the time series.

3.3 Analysis of Regression Results

To address multicollinearity among variables, ridge regression was employed for model estimation. By incorporating the bias parameter *K* to modify the least squares method, ridge regression yields more stable estimates at the cost of some unbiasedness. *K* = 0.000 was selected for regression analysis, with results detailed in Table 2.

Table 2. Ridge Regression Analysis Results

	Regression Coefficient	VIF Value
Constant	-2069.668** (-2.597)	-
Total Population	0.997 (1.437)	2.058
GDP per capita	0.013* (2.291)	3.268
Secondary Industry Value Added as a Percentage of GDP	26.723** (2.914)	1.928
Population Density	401.857** (2.600)	2.066
General Solid Waste Comprehensive Utilization Rate %	-4.298 (-1.154)	1.122
Total Energy Consumption	3.738** (4.907)	2.889
Percentage of fiscal expenditure	4144.050 (0.679)	1.111
Sample size	353	
R ²	0.374	
Adjusted R ²	0.361	
F value	F (7,345) = 29.383, p = 0.000	

* p<0.05 ** p<0.01 (Values in parentheses indicate t-statistic)

The regression results indicate that total energy consumption, per capita GDP, secondary industry share, and population density are the primary drivers of carbon emissions growth in the five northwestern provinces. Among these, total energy consumption is significantly positive at the 1% level with a regression coefficient of 3.738, confirming that energy consumption scale is the core determinant of carbon emissions—each additional 10,000 tons of standard coal increases carbon emissions by 37,380 tons. The secondary industry share and population density are also significant at the 1% level, with regression coefficients of 26.723 and 401.857, respectively. This reflects the significant driving role of an economy dominated by resource-based industries and the spatial concentration of population in carbon emissions. Per capita GDP is significantly positive at the 5% level with a regression coefficient of 0.013, indicating that the five northwestern provinces remain in a developmental stage where economic growth and carbon emissions are not yet decoupled. Total population fails to pass the significance test, suggesting that population concentration explains carbon emissions more effectively than overall population size. The comprehensive utilization rate of general solid waste and environmental protection expenditure did not show significant effects. However, the negative coefficient for the former aligns with theoretical expectations, suggesting the emission reduction potential of solid waste resource utilization remains largely untapped. The latter indicates that the emission reduction effects of environmental fiscal investments may suffer from time lags or efficiency issues. The adjusted R² of the model is 0.361, and the F-test is significant at the 1% level, confirming the model's validity and its ability to adequately explain the variation in carbon emissions across the five northwestern provinces.

In summary, total energy consumption, GDP per capita, secondary industry share, and population density are the primary drivers of carbon emission growth in the five northwestern provinces. All four variables passed significance tests with signs consistent with theoretical expectations. The findings accurately reflect the carbon emission characteristics of the five northwestern provinces as resource-rich regions and heavy industrial bases, validating the model's rationality. Future carbon reduction policies should prioritize enhancing energy efficiency, optimizing industrial structure, and rationally guiding population spatial distribution, while strengthening the effectiveness evaluation of solid waste resource utilization and environmental protection funding.

4 Conclusions and Recommendations

4.1 Conclusions

Based on panel data from prefecture-level cities in the five northwestern provinces from 2011 to 2023, this study systematically analyzed the spatiotemporal characteristics of regional carbon emissions, the decoupling relationship between economic growth and carbon emissions, and its influencing factors. The following key conclusions were drawn:

Regarding the spatiotemporal evolution of carbon emissions, the total emissions across the five northwestern provinces showed an overall upward trend during the study period, though significant regional variations existed. Carbon emissions growth was particularly pronounced in resource-rich areas and heavy industrial bases. In contrast, cities like Tianshui and Dingxi, which underwent earlier industrial transformation or have higher agricultural shares, experienced relatively moderate carbon emission growth.

Regarding the dynamic evolution of decoupling, the relationship between carbon emissions and economic growth in the five northwestern provinces underwent a transformation from relative stability to sharp fluctuations and then to complex differentiation between 2012 and 2023. In 2012, most cities exhibited weak or strong decoupling. 2015 saw a surge in negative decoupling, marking the peak year for decoupling pressures. Decoupling conditions improved in 2019, but by 2023, expansion coupling and expansion negative decoupling once again dominated.

Regression results indicate that total energy consumption, secondary industry share, population density, and per capita GDP are significant drivers of carbon emissions growth in the five northwestern provinces. Among these, total energy consumption is significantly positive at the 1% level with a regression coefficient of 3.738, serving as the core determinant of carbon emissions. Secondary industry share and population density are also significant at the 1% level, with regression coefficients of 26.723 and 401.857, respectively. Per capita GDP is significantly positive at the 5% level with a regression coefficient of 0.013. Total population fails to pass the significance test, indicating that population concentration explains carbon emissions more effectively than overall population size. The comprehensive utilization rate of general solid waste and the proportion of energy conservation and environmental protection expenditures show

no significant effects. However, the negative coefficient for the former aligns with theoretical expectations, suggesting that the emission reduction potential from solid waste resource utilization remains largely untapped.

4.2 Recommendations for Emission Reduction Pathways in the Five Northwestern Provinces' Urban Clusters

Implement carbon emission intensity controls in key industries within resource-rich areas and heavy industrial bases. Establish carbon emission monitoring systems for energy-intensive sectors in cities like Yulin, Hami, Jiayuguan, and Shizuishan, conducting regular energy efficiency benchmarking for coal mining, thermal power generation, coal chemical processing, and steel smelting. Using national industry benchmarks, production lines failing to meet energy efficiency standards for three consecutive years should be required to implement energy-saving upgrades within a specified timeframe. Those remaining non-compliant after upgrades and operating at low capacity utilization should be guided toward orderly market exit. Simultaneously, support enterprises in undertaking low-cost energy-saving projects like waste heat/pressure utilization and circulating water system optimization, leveraging market-based mechanisms such as energy performance contracting to reduce emission reduction costs.

For cities with unstable decoupling, implement categorized guidance and dynamic regulation. For resource-dependent cities like Yulin and Jiayuguan, which have long experienced negative decoupling during expansion, prioritize extending industrial chains and upgrading product structures. Support the coupling of coal chemical industries with green electricity, and encourage steel enterprises to increase scrap steel ratios and develop electric furnace steelmaking. Promote rooftop photovoltaic installations in new industrial parks and guide major consumers like data centers and cold-chain logistics to participate in green electricity trading. For clean energy bases like Hainan Tibetan Autonomous Prefecture, include supporting industries for new energy in carbon emission accounting. New polysilicon and energy storage projects must comply with per-unit product carbon emission limits.

Implement coordinated governance across energy, industry, and spatial planning targeting core drivers. For energy consumption, key energy-consuming entities with annual comprehensive energy consumption exceeding 50,000 tons of standard coal will be subject to energy budget management. For industrial structure, new industrial projects must undergo carbon emission impact assessments, with carbon intensity serving as a binding criterion for project approval. Existing enterprises will be supported in reducing carbon emissions per unit of output through technological upgrades. Population density will be incorporated into urban spatial planning indicators to reasonably define urban development boundaries and prevent emission pressures from excessive population concentration. Efforts will be made to promote the large-scale utilization of fly ash, coal gangue, and smelting slag in building materials production, underground mine backfilling, and road embankment filling. Environmental regulation: Annual performance evaluations will be conducted on fiscal expenditure projects for energy conservation and environmental protection, focusing on assessing the alignment between

funding allocation and emission reduction outcomes. Funding for low-efficiency projects will be promptly redirected.

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