INTI JOURNAL | Vol.2025, Issue 4, No.4
eISSN:2600-7320

A Coupling Coordination Analysis of Population Characteristics and Carbon Emissions in Sichuan Province, China

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Abstract

In the context of global climate change, carbon emissions have become one of the most pressing challenges to sustainable development in human society. This study examines population characteristics and carbon emission trends in Sichuan Province under China's "dual carbon" goals (carbon peaking and carbon neutrality). By establishing an indicator system linking demographic factors—including total population, age structure, urbanization level, income levels, consumption patterns, and population density—to carbon emissions, we applied a coupling coordination model to analyze Sichuan's demographic changes from 2004 to 2021. The results show that while the comprehensive coupling coordination index fluctuated annually, its overall upward trajectory from 0.09 in 2004 to 0.61 in 2021 aligns with the general trend of improved coordination. This indicates significant progress from extreme imbalance to basic coordination. To accelerate achieving the dual carbon targets, it is crucial to strengthen population management policies, develop measures addressing demographic structures, enhance population quality, and implement targeted strategies for sustainable development.

Keywords

Carbon emission, Population characteristic index, Coupling coordination degree

Introduction

In the context of global climate change, carbon emissions have become one of the severe challenges facing the sustainable development of human society, with the impact of demographic changes on carbon emissions receiving significant social attention. For instance, shifts in consumption patterns lead to increased energy demand, thereby affecting the growth of carbon emissions (Chen & Yang, 2013). With the accelerated advancement of urbanization and industrialization, Sichuan Province's carbon dioxide emissions may continue to rise rapidly in the future (Jiang & Huang, 2016). To achieve the "dual carbon" goals, the Chinese government has introduced a series of important policies and measures across various fields including environmental protection, economic development, and social welfare, such as enhancing environmental education and raising public awareness of ecological conservation (Feng & Liu, 2016). Therefore, this study utilizes data from the 2004 to 2021 editions of the China Urban Statistical Yearbook and Sichuan Statistical Yearbook, employing a coupling coordination model to explore the relationship between demographic characteristics and carbon

Submission: 26 August 2025; **Acceptance:** 1 November 2025; **Available online:** November 2025

emissions in Sichuan Province. The aim is to propose actionable policy recommendations for government decision-making to accelerate the realization of dual carbon targets.

Methodology

Guided by the principles of systematicness, scientific rigor, objectivity, and practical applicability in indicator selection, and considering the criteria of clear objectives, comprehensive coverage, representativeness, and operational feasibility, we developed an integrated index system encompassing total population, birth rate, mortality rate, age structure, urbanization rate, per capita GDP, per capita consumption, population density, and carbon emissions (Feng & Wang, 2007).

The coupling coordination degree model quantitatively analyzes the correlation and coordination levels between different systems through a series of indicators and computational methods. Based on systems science theory, this model aims to reveal synergistic relationships between D_i systems. It is commonly used to evaluate the coordinated development status among various elements or subsystems in multiple fields such as economy-environment and society-ecology. The coupling coordination degree (CDD) function is expressed as:

$$D_i = \sqrt{C_i \times T_i} \qquad (2-1)$$

among ：

$$C_i = \left\{ \frac{\prod_{i=1}^{n} U_i}{\left(\frac{i}{n}\sum_{i=1}^{n} U_i\right)^n} \right\} \qquad (2-2)$$

$$T_i = \sum_{i=1}^{n} W_i \times U_i, \sum_{i=1}^{n} W_i = 1 \qquad (2-3)$$

In Formula 2-2, $C_iU_iT_iW_iU_i$ *and* $W_iZ_{ij}E_j$ the coupling degree is defined as a value ranging from (0 to 1), where higher values indicate tighter coupling effects. The comprehensive evaluation value for each year is calculated in Formula 2-3, where represents the coordination degree and is the weighting factor. Both calculations utilize the entropy method. Prior to applying the entropy calculation, standardized processing of indicators is required. This study employs z-score normalization to standardize the data. According to the entropy method, the entropy value corresponding to the j-th indicator in any given year is:

$$E_j = -k\sum_{i=1}^{n}\left(Z_{ij} \times \ln Z_{ij}\right) \qquad 2-4$$

In the formula, $i = 1, 2,..., n$; $j = 1, 2,..., m$.

The calculation formula of entropy value method weight is:

$$W_j = \frac{1 - e_j}{\sum_{j=1}^{m} e_j} \qquad 2-5$$

According to the standardized value and weight of each indexU_i, the comprehensive score of each year can be further calculated:

$$U_i = \sum_{j=1}^{m} w_{ij} z_{ij} \qquad 2-6$$

Results and Discussion

Based on the data from the 2004 to 2021 China Urban Statistical Yearbook and Sichuan Statistical Yearbook regarding total population, birth rate, death rate, age structure, urbanization rate, per capita GDP, per capita consumption, population density, and carbon emissions, the weighting coefficients were calculated using formulas 2-4 and 2-5 through SPSS software, as shown in Table 1. According to formula 2-6, the comprehensive evaluation values for each year were calculated, as presented in Table 2. The coupling degree, coordination degree, and coupled coordination degree were determined using formulas 2-1, 2-2, and 2-3, respectively, as illustrated in Table 2. This study combines literature to establish a classification standard for coupling coordination levels, as detailed in Table 3 (Chen & Ge, 2022).

Table 1. Summary of weight calculation results by entropy method

project	Information entropy value e	Information utility value d	weight coefficient w
Population per 10,000	1.0000	0.0000	0.02%
birth rate /%	0.9977	0.0023	1.78%
death rate /%	0.9990	0.0010	0.79%
Proportion of children (%)	0.9984	0.0016	1.28%
Proportion of elderly population/%	0.9999	0.0001	0.08%
proportion of aged population /%	0.9949	0.0051	4.00%
urbanization rate /%	0.9940	0.0060	4.78%
Per capita GDP/ten thousand yuan	0.9428	0.0572	45.27%
Per capita consumption / 10,000 yuan	0.9525	0.0475	37.60%
Population density	0.9999	0.0001	0.08%
Carbon emissions/ten thousand tons	0.9946	0.0054	4.31%

Table 2. Comprehensive score table of U_i、C_i、T_i、D_i each year

year	Overall score (U)	Coupling degree C value	Coordinate index T value	Coupling coordination degree D value	Coordination level	Degree of coupling and coordination
2004	12.03	0.246	0.031	0.088	1	Extreme dislocation
2005	11.87	0.434	0.064	0.166	2	major maladjustment
2006	12.33	0.591	0.086	0.226	3	Moderate dysregulation
2007	14.21	0.665	0.132	0.296	3	Moderate dysregulation
2008	15.57	0.846	0.182	0.392	4	Mild impairment
2009	17.36	0.800	0.234	0.433	5	On the verge of breakdown
2010	18.04	0.524	0.270	0.377	4	Mild impairment
2011	18.28	0.604	0.346	0.457	5	On the verge of breakdown
2012	18.90	0.721	0.394	0.533	6	A patchwork of efforts
2013	18.70	0.819	0.469	0.620	7	Primary coordination
2014	19.85	0.801	0.513	0.641	7	Primary coordination
2015	18.08	0.817	0.535	0.661	7	Primary coordination
2016	18.24	0.849	0.592	0.709	8	Intermediate coordination
2017	17.74	0.812	0.666	0.735	8	Intermediate coordination
2018	19.26	0.874	0.758	0.814	9	Good coordination
2019	20.51	0.847	0.835	0.841	9	Good coordination
2020	20.25	0.525	0.854	0.669	7	Primary coordination
2021	20.74	0.393	0.950	0.611	7	Primary coordination

Table 3. coupling coordination degree classification criteria

Range of coupling coordination degree D value	Coordination level	Degree of coupling and coordination
[0.0~0.1)	1	Extreme dislocation
[0.1~0.2)	2	major maladjustment
[0.2~0.3)	3	Moderate dysregulation
[0.3~0.4)	4	Mild impairment
[0.4~0.5)	5	On the verge of breakdown
[0.5~0.6)	6	A patchwork of efforts
[0.6~0.7)	7	Primary coordination
[0.7~0.8)	8	Intermediate coordination
[0.8~0.9)	9	Good coordination
[0.9~1.0]	10	Quality coordination

The comprehensive coupling coordination degree of Sichuan Province has shown varying annual fluctuations, yet its changing trends align closely with the overall score, demonstrating an upward trajectory from 0.09 in 2004 to 0.61 in 2021. This progression marked a transition from extreme imbalance to basic coordination. Specifically, during the first upward phase (2004-2009), economic growth drove increased energy consumption and consequently higher carbon emissions. During this period, Sichuan experienced moderate growth in population, per capita GDP, and per capita consumption, while urbanization likely accelerated. The coordination degree declined between 2009 and 2010, dropping from 0.59 to 0.42 – a shift from barely coordinated to near-disordered. The second upward phase occurred between 2011 and 2019, reaching a peak of 0.84. Notably, both 2018 and 2019 saw intermediate coordination levels. During this period, Sichuan actively promoted economic development through increased investment and industrial upgrading initiatives, achieving GDP growth. However, as the province prioritized ecological conservation, coordination began declining again. The degree reached basic disorder in early 2020 and dropped by 0.06 in 2021.

Conclusion

The analysis shows that Sichuan Province's comprehensive coupling coordination index has shown varying levels of fluctuation across different years, yet its overall upward trajectory aligns with the general trend in composite scores, rising from 0.09 in 2004 to 0.61 in 2021. The progression from extreme imbalance to basic coordination demonstrates how environmental policies have facilitated better alignment between population characteristics and carbon emissions in Sichuan. To enhance population control and workforce quality improvement, the province should implement population structure-related policies that encourage family planning initiatives and educational advancement.

Acknowledgements

There is no grant or funding bodies to be acknowledged for preparing this paper.

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