

Study on Regional Differences and Spatial Convergence Characteristics of Carbon Emission Intensity in Jilin Province

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Abstract:

In the context of “carbon peak, carbon neutral”, carbon reduction and emission reduction is a realistic need for China to achieve high-quality economic development in the future, and it is the fundamental way to promote the sustainable development of enterprises. The study of regional carbon emission intensity is an important hand to achieve low-carbon industrial transformation and accelerate high-quality development. This paper combines the carbon emission data and economic and social data of Jilin Province, and reveals the spatial differences and convergence characteristics of carbon emission intensity in Jilin Province through the methods of *Dagum Gini coefficient* decomposition method, coefficient of variation and spatial convergence model. The results of the study show that the *Gini coefficient* of carbon emission intensity in Jilin Province and various regions shows a more obvious imbalance, and the degree of this imbalance has increased in general. The carbon emission intensity of Jilin Province as a whole has certain σ -convergence characteristics, and the σ -convergence characteristics of the eastern, western and central regions are not obvious. There are different degrees of absolute β -convergence of carbon emission intensity in Jilin Province as a whole, the western region and the central region; there is conditional β -convergence in Jilin Province and all regions, and the speed of conditional β -convergence is significantly faster than that of absolute β -convergence, and there are differences in the factors of the carbon reduction effect in different regions and there is a certain degree of spatial heterogeneity in the influence. It provides a basis for the formulation of carbon emission reduction policies in Jilin Province, and guides the Jilin Provincial Government to consider carbon emission when planning economic development and to improve environmental protection.

Keywords:

Dual Carbon, Carbon Emission Intensity, Regional Differences, Spatial Convergence, Jilin Province

1. Introduction

The report of the Twentieth National Congress of the Communist Party of China points out that achieving “dual-carbon” is a broad and profound economic and social systemic change. As global climate change intensifies, reducing carbon emissions has become an important issue for all countries to address. In order to achieve the sustainable development goals and respond to climate change, China has put forward a strategy to achieve the “dual-carbon” goal, aiming to peak carbon emissions and achieve carbon neutrality by 2060. As an important component of global carbon emissions, the intensity of carbon emissions and regional differences in each region are important for achieving the “double carbon” goal. As an important industrial base and agricultural province in Northeast China, the intensity and spatial distribution of carbon emissions in Jilin Province have a significant impact on the achievement of the “dual carbon” goal. However, there are relatively few systematic studies on the regional differences and spatial convergence characteristics of carbon emission intensity in Jilin Province. Therefore, this study will explore the spatial distribution characteristics of carbon emission intensity in Jilin Province, provide solid scientific support and strategic recommendations for carbon emission reduction in Jilin Province, and further promote the sustainable development of the region.

2. Research Methodology and Data Sources

2.1. Carbon Emission Intensity Measurement

Carbon dioxide emissions are measured with reference to Zhao Guimei et al. [9] Carbon intensity is the ratio of total CO₂ emissions to the level of economic development. The calculation formula is:

$$CI_j = \frac{CE_j}{GDP_j}, \quad j = 1, 2, 3, \dots, 30 \quad (1)$$

Where, j represents the observed provinces and regions, CI represents carbon intensity; CE represents carbon dioxide emissions; and GDP represents the level of economic development.

2.2. Decomposition of regional differences

In this paper, we use *Dagum's Gini coefficient* decomposition method to decompose the regional differences in carbon emission intensity in Jilin Province. *Dagum* (1997) decomposed the overall *Gini coefficient* into three components according to the subgroup decomposition method: the contribution of intra-regional disparity G_w , the contribution of inter-regional disparity G_b and the contribution of hypervariable intensity G_t , and it satisfies the $G = G_w + G_b + G_t$, which is calculated by the following formula:

$$G = \frac{\sum_{j=1}^k \sum_{h=1}^k \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |y_{ji} - y_{hr}|}{2n^2 \bar{y}_{ji}} \quad (2)$$

where G is the overall Gini coefficient, $y_{ji}(y_{hr})$ is the carbon intensity within region $j(h)$, i, r represent different cities within the economic region ($j(h)$), n is the number of cities and $\bar{y}_{ji}$ is the average of the carbon intensity of all the cities, $n_j(n_h)$ denotes the number of cities within the region $j(h)$, and k denotes the number of dividing areas.

2.3. Convergence model

Carbon emission intensity belongs to a kind of efficiency indicator, and with the steady progress of carbon peak and carbon neutrality, carbon emission intensity is likely to converge to a certain steady state, so it is very suitable to use the convergence model to study the characteristics of the long-term change of the carbon emission intensity of China's cities and major strategic regions. Common convergence models are σ -convergence and β -convergence, and this paper refers to Wang, Dong et al. [6] and Zhang, Zhuoqun et al. [3]

(1) σ converges

σ convergence refers to the tendency of the deviation of the carbon emission intensity of each region to decrease over time. In this paper, the coefficient of variation is used to measure the σ convergence, and the calculation formula is as follows:

$$\sigma = \frac{\sqrt{\frac{\sum_{i=1}^{N_j} (CMI_{ij} - \overline{CMI}_{ij})^2}{N_j}}}{\overline{CMI}_{ij}} \quad (3)$$

where CMI_{ij} denotes the carbon intensity of city i in region j , $\overline{CMI}_{ij}$ denotes the mean value of carbon intensity in region j , and N_j denotes the number of cities in region j .

(2) β -convergence

β -convergence refers to the fact that with the advance of time, the region with higher carbon emission intensity has a higher rate of decrease to catch up with the region with lower carbon emission intensity, and the gap between the two regions gradually narrows, and finally reaches the same steady state level. β -convergence can be divided into absolute β -convergence and conditional β -convergence. Absolute β -convergence refers to the tendency of convergence of carbon emission intensity between regions without considering a series of factors that have an important influence on carbon emission intensity. The absolute β convergence model is as follows:

$$\ln \left(\frac{CI_{i, t+1}}{CI_{it}} \right) = \alpha + \beta \ln (CMI_{i, t}) + \mu_i + \eta_t + \varepsilon_{it} \quad (4)$$

$$\ln \left(\frac{CI_{i, t+1}}{CI_{it}} \right) = \alpha + \beta \ln (CMI_{i, t}) + \rho W \ln \left(\frac{CMI_{j, t+1}}{CMI_{j, t}} \right) + \mu_i + \eta_t + \varepsilon_{it} \quad (5)$$

$$\ln \left(\frac{CI_{i, t+1}}{CI_{it}} \right) = \alpha + \beta \ln (CMI_{i, t}) + \mu_i + \eta_t + \varepsilon_{it}, \quad \varepsilon_{it} = \eta W \varepsilon_{jt} + \sigma_{it} \quad (6)$$

$$\ln \left(\frac{CI_{i, t+1}}{CI_{it}} \right) = \alpha + \beta \ln (CMI_{i, t}) + \rho W \ln \left(\frac{CMI_{j, t+1}}{CMI_{j, t}} \right) + \theta W \ln (CI_{j, t}) + \varepsilon_{it} \quad (7)$$

Eqs. (4) to (7) are the OLS, SAR, SEM and SDM models, respectively. Where CI is the carbon emission intensity, i represents province, t represents time, $CI_{i, t+1}$ and CI_{it} are the carbon emission intensity of province i at time $t+1$ and time t , respectively, W is the geographic distance spatial weight matrix, ρ is the coefficient of the spatial lag term, η is the coefficient of the spatial error term, θ is the coefficient of the spatial interaction term, μ_i and η_t represent the individual effect and time effect, respectively, and ε is the random perturbation term obeying the independent and homogeneous distribution. β is the convergence coefficient, if β is significantly negative, it indicates

that there is β -convergence of carbon emission intensity in the economic zone, and vice versa, it shows divergence.

The speed of β -convergence v is used to indicate the speed of catching up with the high level of carbon emission intensity in the low level region, as shown in equation (8).

$$v = -\frac{\ln (1+\beta)}{T} \quad (8)$$

Regarding the choice of control variables, drawing on the relevant literature, the ones chosen are shown in Table 1:

Table 1. Definition of Variables.

Variable Types	Notation	Variable Names	Variable Definition
Explanatory Variables	EC	Carbon Emission Intensity	Carbon Emissions/GDP (tonnes per million)
Explanatory variables (control variables)	IS	Industrial Structure	Secondary and Tertiary Output/GDP
	PGDP	Level of Economic Development	GDP Per Capita (million yuan)
	UR	Urbanisation Level	Urban Population/Total Population
	GOV	Government Action	Fiscal Expenditure/GDP
	PAT	Level of Technological Innovation	Number of Patents Granted Per 10,000 Persons (pieces)
	OPEN	Egyptian Open-door Policy	Import/Export Trade/GDP
	EI	Energy Structure	Energy Production Per Capita (tonnes)

2.4. Data sources

This paper adopts panel data of nine prefecture-level cities in Jilin Province from 2009 to 2023. The data come from the Jilin Statistical Yearbook, China Energy Statistical Yearbook and the National Economic and Social Development Statistical Bulletin of each prefecture-level city in all years.

3. Analysis of Regional Differences in Carbon Emission Intensity in Jilin Province

3.1. Overall Level of Carbon Emission Intensity in Jilin Province

Jilin Province is one of the important industrial bases in China, and the overall level of carbon emission intensity is of great significance to the sustainable development of the region. Compared with other provinces, the level of carbon emission intensity in Jilin Province during 2009-2023 is relatively low, which is mainly affected by the industrial structure of the region. Jilin Province is dominated by agriculture and light industry, and its carbon emission intensity is low compared to provinces with heavy industry. However, with the acceleration of industrialisation in Jilin Province, carbon emission intensity still needs to be further reduced to achieve the goal of sustainable development. Compared with the national average, Jilin's carbon emission intensity is slightly lower than the national average. This indicates that Jilin Province has made some achievements in carbon emission management, but still needs to make greater efforts to further reduce carbon emission intensity and promote the development of a low-carbon economy. As can be seen from Figure 1, the carbon emission intensity of Songyuan City has been the lowest in the province in the past 15 years, and Siping City has been the highest in the province.

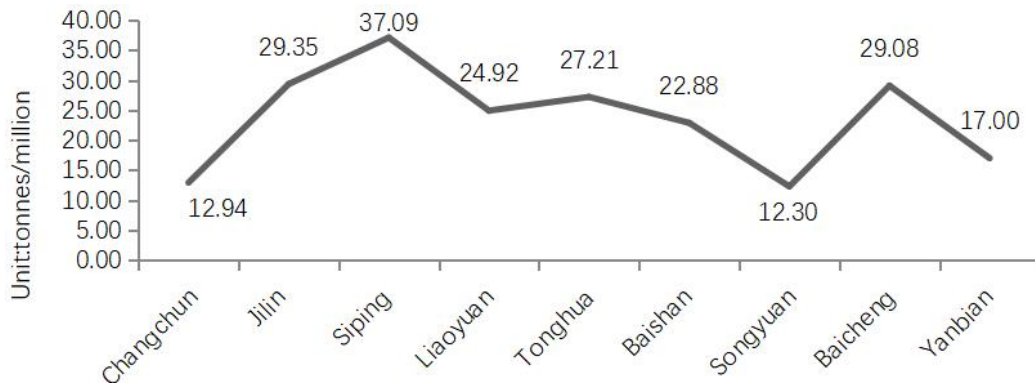


Figure 1. Carbon emission intensity of each city in Jilin Province during 2009-2023.

3.2. Overall difference of carbon emission intensity and its decomposition in Jilin Province

Figure 2, Figure 3, Figure 4 and Table 2 show the results of the *Dagum Gini coefficient* and contribution rate of carbon emission intensity in Jilin Province. The overall *Gini coefficient* of carbon emission intensity in Jilin Province shows a more obvious imbalance, and the degree of this imbalance has increased in general. Taking 2015 as the inflection point, it shows the “inverted V” type change of “first falling and then rising, then falling and then rising”. In terms of the source of variation, the contribution of intra-regional variation ranges from 23% to 31%, the contribution of inter-regional variation ranges from 3% to 66%, and the contribution of hypervariable density ranges from 8% to 66%. In terms of mean values, the mean value of the overall *Gini coefficient* of carbon emission intensity in Jilin Province from 2009 to 2023 is 0.207, and the *Gini coefficient* of hypervariable density is 0.085, contributing 45.83 per cent to hypervariable density, which is the main source of the overall difference, while the contribution rates of intra-region differences and inter-region differences are 28.38 per cent and 25.80 per cent, respectively. It means that the way of dividing the regions in Jilin Province can effectively distinguish different types of cities with strong rationality.

Table 2. Sources of overall difference in carbon emission intensity and contribution rate results for Jilin Province, 2009-2023.

Year	Gini Index				Contribution Rate (%)		
	Population	Within-group inequality (Gw)	Between-group inequality (Gb)	Hypervariance density (Gt)	Population	Within-group inequality (Gw)	Between-group inequality (Gb)
2009	0.203	0.048	0.111	0.044	23.87	54.70	21.43
2010	0.151	0.041	0.032	0.078	27.39	21.08	51.53
2011	0.178	0.048	0.043	0.086	27.29	24.39	48.32
2012	0.174	0.048	0.038	0.089	27.28	21.52	51.20
2013	0.168	0.048	0.029	0.09	28.78	17.56	53.66
2014	0.152	0.046	0.006	0.1	30.26	3.95	65.79
2015	0.514	0.131	0.337	0.046	25.39	65.65	8.96
2016	0.16	0.048	0.021	0.092	29.70	12.85	57.46
2017	0.165	0.047	0.037	0.081	28.70	22.57	48.73
2018	0.167	0.049	0.03	0.088	29.22	18.19	52.59
2019	0.178	0.052	0.027	0.099	28.99	15.40	55.61
2020	0.205	0.063	0.042	0.101	30.56	20.50	48.94
2021	0.226	0.066	0.068	0.092	29.28	30.02	40.70

2022	0.232	0.068	0.07	0.094	29.36	30.06	40.58
2023	0.237	0.07	0.068	0.099	29.63	28.49	41.89
average value	0.207	0.058	0.064	0.085	28.38	25.80	45.83

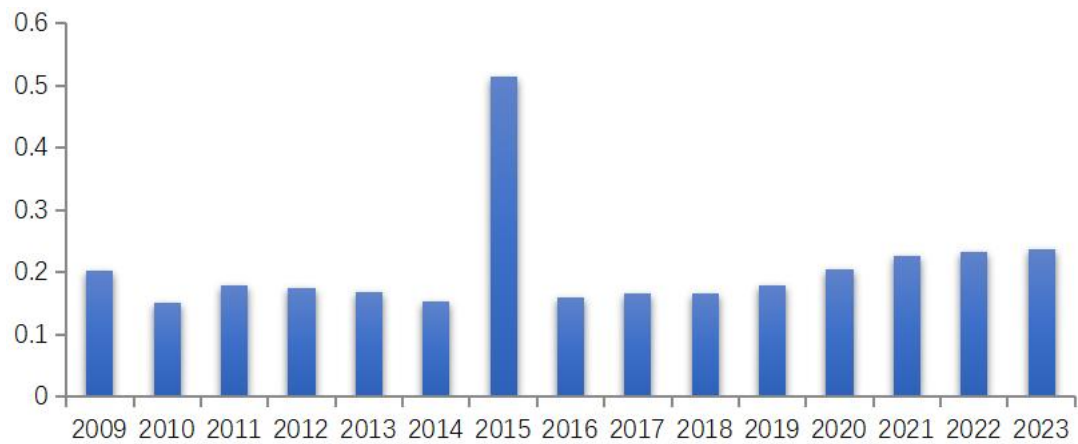


Figure 2. Changes in overall carbon emission intensity in Jilin Province, 2009-2023.

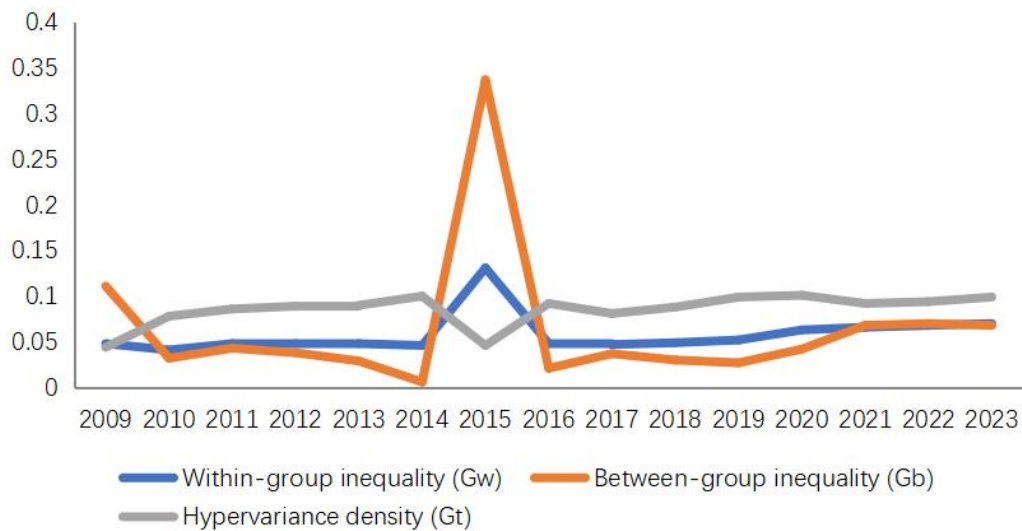


Figure 3. Changes in Gini coefficient of carbon emission intensity in Jilin Province, 2009-2023.

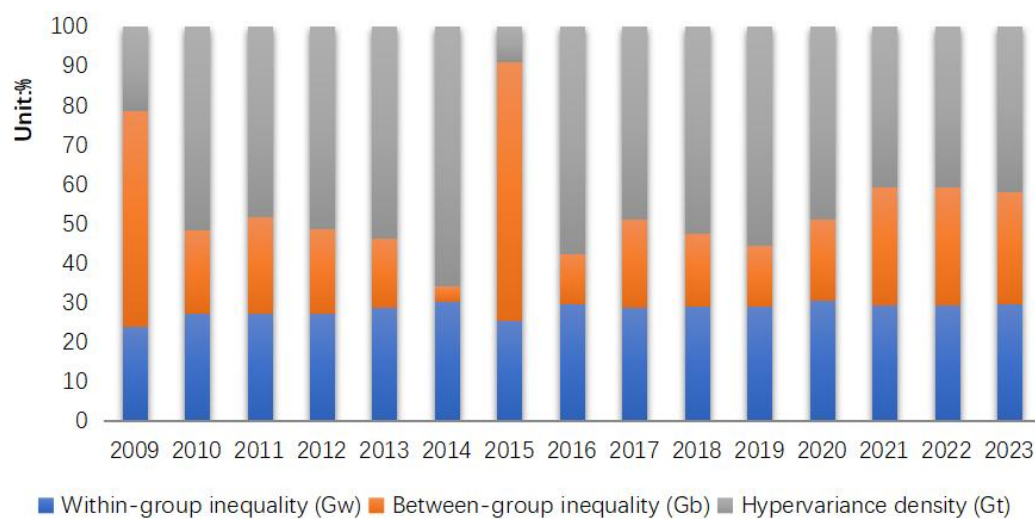


Figure 4. Changes in the contribution of carbon emission intensity in Jilin Province, 2009-2023.

3.3. Differences in Carbon Emission Intensity within Regions in Jilin Province

Jilin Province is divided into the following regions: Baishan City, Tonghua City and Yanbian Korean Autonomous Prefecture in the east; Songyuan City, Baicheng City and Siping City in the west; and Changchun City, Jilin City and Liaoyuan City in the central region. The *Dagum Gini coefficient* is used to measure the degree of intra-group differences in carbon emission intensity in each region of Jilin Province, and the year-by-year results are reported in Figure 5. The *Dagum Gini coefficient* decomposition of the differences in carbon emission intensity shows the intra-group *Gini coefficient* Gw values in each year in each region of Jilin Province and the inter-group *Gini coefficient* values between the two regions in each year, but only some of the information is shown due to the large amount of data. Overall, the central region of Jilin Province has the highest intra-group *Gini coefficient* value for carbon intensity, implying that the phenomenon is most pronounced among cities in the central region, followed by the western region, and then the eastern region. The intra-group *Gini coefficient* value in the western region shows a decreasing trend, which means that the phenomenon among cities in the western region has been decreasing in the last 20 years. However, in the central and eastern regions, the phenomenon is on the rise.

Under the goal of “double carbon”, the carbon emission intensity in Jilin Province shows some regional differences. The *Gini coefficient* within the group in the western part of Jilin Province decreases, indicating that carbon emissions are more balanced and development is more coordinated within the region. This may be due to the optimisation of the industrial structure, which has eliminated some high-carbon emitting traditional industries and promoted the development of green and low-carbon industries, thus reducing the variability of carbon emission intensity. In contrast, the *Gini coefficients* within the group in central and eastern Jilin Province have risen, suggesting that carbon emissions are more uneven within the region. As Jilin Province continues to develop, with the opening of high-speed railways and the development of tourism, carbon emissions are increasing, which may be due to the serious imbalance in regional development in these regions, and the more homogeneous economic structure of some regions, which relies on high-carbon emitting industries, leading to greater variability in carbon emission intensity. In addition, the central and eastern regions may be facing certain difficulties in industrial restructuring, which has led to a higher rate of growth in carbon emission intensity than in some regions, and may face more challenges in this process.

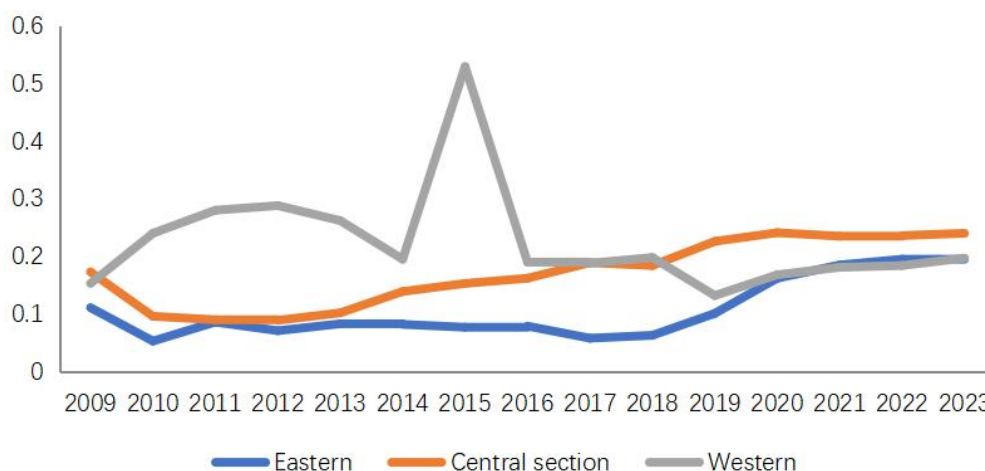


Figure 5. Changes in intra-group differences in carbon emission intensity by region in Jilin Province.

3.4. Differences in Carbon Emission Intensity between Regions in Jilin Province

Figure 6 demonstrates the changes in the overall difference in carbon emission intensity between regions in Jilin Province from 2009-2023. The inter-regional difference between the central and western regions of Jilin Province is the largest, with a mean *Gini coefficient* of 0.256, followed by the inter-regional between the eastern and western regions, and the eastern and central regions, with mean *Gini coefficients* of 0.235 and 0.166, respectively. Specifically, the *Gini coefficient* of the carbon emission intensity between the eastern and central regions of Jilin Province shows a decreasing trend from 2009 to 2012, with the *Gini coefficient* decreasing from 0.164 in 2009 to 0.089 in 2012, and an increasing trend from 2012 to 2023, with the *Gini coefficient* increasing from 0.089 in 2012 to 0.266 in 2023. The *Gini coefficient* of carbon emission intensity between the eastern and western regions is similar to that between the central and western regions, showing an “inverted V” trend. This shows that the imbalance of carbon emission intensity among regions in Jilin Province is relatively prominent, because under the “dual-carbon” goal, there are obvious differences in economic development, industrial layout, industrial structure, resource endowment and other factors among regions in Jilin Province, and there are also differences in the intensity of energy consumption, the work of emission reduction and the speed of advancement among provinces and municipalities. The intensity of energy consumption and the speed of emission reduction and promotion among provinces and cities are also inconsistent.

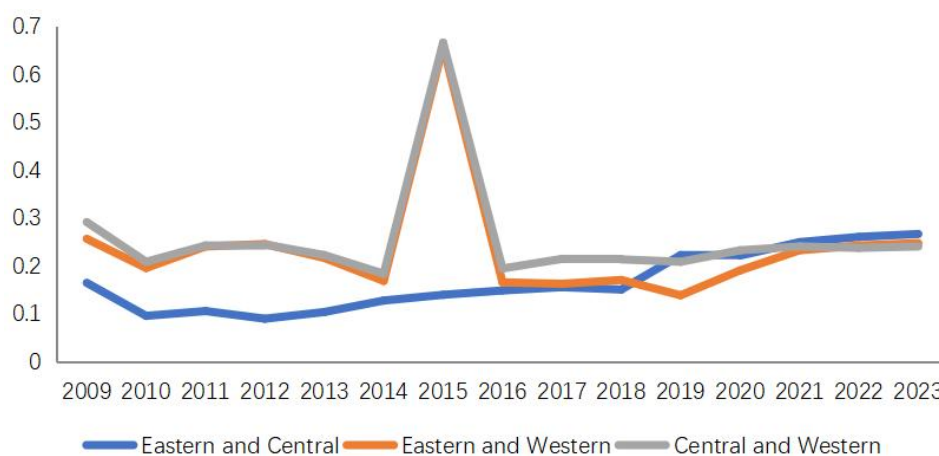


Figure 6. Changes in inter-group differences in carbon emission intensity by region in Jilin Province.

4. Convergence Analysis of Carbon Emission Intensity in Jilin Province

4.1. σ -convergence of carbon emission intensity in Jilin Province

Figure 7 shows the coefficients of variation of carbon emission intensity between Jilin Province and various regions and their evolution trends from 2009 to 2023. From the perspective of Jilin Province as a whole, the coefficient of variation of carbon emission intensity shows the change process of “gentle decline - sharp rise - sharp decline - gentle rise”, with the lowest point occurring in 2014, from 0.232 in 2009 to 0.132 in 2023, the variability of carbon emission intensity is further enlarged, and the

end value is lower than the beginning value, is lower than the beginning value, and there is a σ -convergence feature. At the regional level, the values of the coefficient of variation in the eastern, western and central regions of Jilin Province increase from 0.256, 0.377 and 0.392 in 2009 to 0.493, 0.444 and 0.543 in 2023, respectively, with the ending values increasing compared with the beginning values, and there is no σ -convergence feature. Jilin Province as a whole has certain σ -convergence characteristics, and σ -convergence characteristics are not obvious in the eastern region, western region and central region.

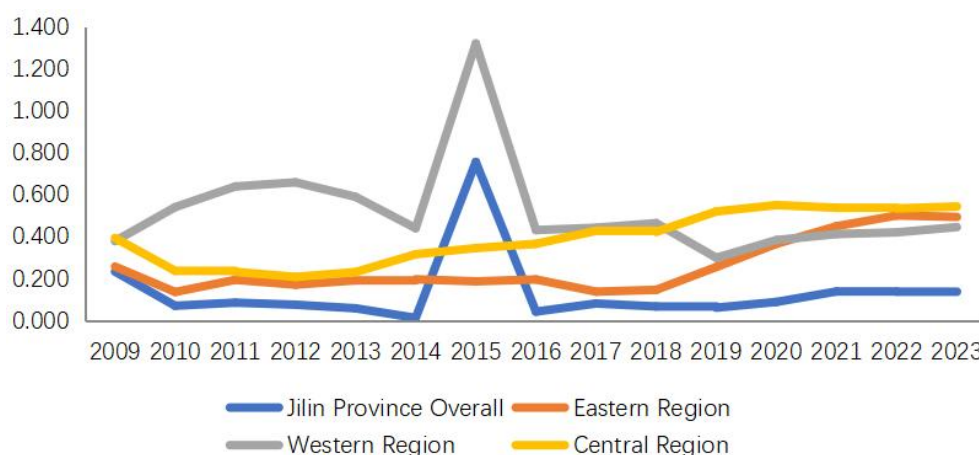


Figure 7. Results of σ -convergence of carbon emission intensity between Jilin Province and each region.

Under the “dual-carbon” goal, due to the different progress of urban energy consumption and industrial structure transformation, the eastern region is characterised by tourism and service industry, while developing special agriculture, promoting the combination of national culture and economy, and promoting the development of regional tourism economy, and the difference in urban carbon emission intensity is narrowing. At the same time, the region is committed to improving energy use efficiency and implementing effective energy conservation and emission reduction measures to cope with the pressure of carbon emissions brought about by rapid economic development. The σ -convergence coefficient of urban carbon emission intensity is higher in the central region because in recent years, the central region has been transforming to an industrial structure based on new materials and green chemicals, promoting the combination of information technology and manufacturing, promoting intelligent manufacturing and R&D innovation, focusing on upgrading the level of technology and environmental protection standards, and developing new industries, such as new energy automobiles and the recycling economy, so that the level of energy utilisation efficiency and industrial development is higher and energy saving and emission reduction measures have been effectively implemented. Measures have been effectively implemented on the ground, while other cities are relatively lagging behind in energy consumption and industrial development, which has led to an increase in the degree of differentiation in carbon emission intensity; in the western region, in the field of agriculture and food processing, it is promoting the combination of agricultural industrialisation and modern logistics, the development of deep-processing of agricultural products and agricultural science and technology, focusing on modern agriculture, promoting the combination of agricultural science and technology and informatisation, and the development of agricultural product processing as well as accelerating the rural economic transformation, the difference between urban industrial transformation and

energy structure is small, and its urban carbon emission intensity σ -convergence coefficient stays at a low level.

3.2. Absolute β -convergence of carbon emission intensity in Jilin Province

The results of the absolute β convergence test of carbon emission intensity between Jilin Province and regions from 2009 to 2023 are shown in Table 3. Since there may be spatial effects of different patterns of carbon emission intensity in different regions, the LM test is first used to determine whether there are spatial autocorrelation effects in the absolute β convergence of carbon emission intensity between Jilin Province and various regions, and then the Wald test and the LR test are used to select the optimal form of spatial model.

The results show that, firstly, the β -convergence coefficients of carbon emission intensities in Jilin Province as a whole, the western region, and the central region are all significantly negative at the 1% level, i.e., there are varying degrees of absolute β -convergence of urban carbon emission intensities, which also indicates that without controlling for a series of economic and social influences, the urban carbon emission intensities will ultimately converge to their respective steady states over time. The eastern region fails the significance test and returns to the traditional convergence model (OLS). In the long run Jilin Province and the regions will converge to their respective steady state levels. Combined with the fact that the carbon emission intensity declines in Figure 1, even though the coefficients of variation of the individual research objects increase in the short term (see Figure 7), the trend of the overall decline in the carbon emission intensity and the long-term convergence has already appeared. Second, from the point of view of the convergence speed, Jilin Province has the fastest convergence speed, the central region has the slowest convergence speed, and only the eastern region does not have absolute β -convergence, which shows that the intra-regional coordination effect is the most obvious in Jilin Province in terms of promoting the synergistic management of carbon emission reduction and pollution. There is a spatial lag of the explanatory variables in the western region of Jilin Province, a spatial error lag in Jilin Province as a whole, and no spatial effect exists in the eastern region by applying the ordinary panel model to carry out the absolute β convergence analysis.

Table 3. Absolute β -convergence test results of carbon emission intensity between Jilin Province and regions

Variant	Jilin Province as a whole		Eastern part	Western Region		Central Region	
	OLS	SEM	OLS	OLS	SAR	OLS	SDM
β	-1.013*** (-10.74)	-1.017*** (-11.91)	-0.204 (-1.39)	-1.095*** (-5.75)	-0.610*** (-5.13)	-0.311*** (-2.03)	-0.830*** (-4.32)
p/λ	-	-0.309* (-1.68)	-	-	-0.691*** (-7.00)	-	-0.445*** (-2.75)
ν	0.047	0.047	0.012	0.049	0.032	0.018	0.040
R^2	0.0569	0.0385	0.0573	0.0698	0.0309	0.0698	0.0165
N	135	135	45	45	45	45	45

Note: * * *, * * and * denote significance at the 1%, 5% and 10% levels, respectively, with t -statistics in parentheses and rates of convergence in %.

3.2. Conditional β -convergence of carbon emission intensity in Jilin Province

The results of the conditional β -convergence test for the carbon emission intensity of Jilin Province and the regions in 2009-2023 with the addition of control variables are shown in Table 7. The results show that, first, conditional β convergence exists in Jilin Province and all regions. The convergence coefficients β of Jilin province and regions are all significant at 1% confidence level, indicating that after considering the economic development level, industrial structure, technological level, open-door level, technological innovation level, governmental behaviour, urbanization level, energy structure and other factors, the tendency for the carbon emission intensity of Jilin province and regions to converge to their respective steady state levels in the long run is still present. Secondly, in terms of the speed of convergence, compared with the absolute β -convergence, the speed of conditional β -convergence is accelerated in all regions, indicating that the control variables and spatial effects promote the convergence of urban carbon emission intensity, which is conducive to the spatial convergence of carbon emission intensity. Third, Jilin Province and all regions show different spatial effects, but the spatial effects of individual regions change compared with the absolute β -convergence analysis. The types of spatial effects in Jilin province as a whole, the western region, and the central region did not change, and the form of spatial correlation in the eastern region changed from OLS to SEM, and ρ/λ was significantly negative at the 10% level. It indicates that the rate of change of carbon emission intensity has a negative spatial spillover effect, which has a direct relationship with the highly polluting, energy-consuming and emission-intensive industrial enterprises in Jilin Province. In addition, there is a spatial lag of the explanatory variables in the western part of Jilin Province, and a spatial error lag in Jilin Province as a whole and the eastern part. Fourthly, from the point of view of control variables, conditional beta convergence analysis shows a significant increase in the R^2 of all models compared with absolute beta convergence analysis after adding control variables, which indicates that the selection of control variables is scientific and effective, and that there is a significant difference in the influencing factors of the carbon emission intensity between Jilin Province and the regions. Taking Jilin Province as the research object, the level of economic development and energy structure have a significant negative impact on the rate of change of carbon emission intensity, i.e., the real level of per capita GDP and import and export trade can effectively promote the convergence of carbon emission intensity to the low value; the industrial structure and governmental behaviours have a significant positive impact on the rate of change of carbon emission intensity, i.e., the output value of the secondary and tertiary industries and the financial expenditure can effectively promote the convergence of carbon emission intensity to the high value; while the urbanization level has a significant increase in R^2 compared with the absolute β convergence analysis. There is no significant effect on the rate of change of carbon emission intensity of urbanisation level, technological innovation level and openness level. It is worth noting that this does not mean that the level of urbanisation, technological innovation and openness to the outside world have no effect on carbon emission intensity, but that increasing the number of urban population, the number of patents granted, and the import and export trade can not promote the convergence of carbon emission intensity to a low value or a high value. Sub-regionally, there is some spatial heterogeneity in the impact of different drivers on urban carbon emission intensity. In the eastern part of Jilin Province, the level of economic development, urbanisation, technological innovation, and opening up to the outside world all have a significant negative impact; government behaviour has a significant positive impact. With the increase of per capita GDP, the optimisation of industrial structure and

technology further reduces the carbon emission intensity. The concentration of urban population improves the efficiency of resource utilisation and facilitates the implementation of energy-saving and emission reduction measures. Technological innovation promotes low-carbon technology and industrial upgrading, reducing carbon emissions per unit of output. Import and export trade facilitated technology transfer and the adoption of international standards, further reducing carbon emissions. However, the significant positive impact of fiscal revenues suggests that government investment in infrastructure development and energy-intensive industries has increased carbon emissions. This suggests that the government needs to optimise the fiscal expenditure structure and strengthen the guidance of the green economy. In the western region of Jilin Province, industrial structure, technological innovation level, and energy structure all have significant negative impacts; government behaviour has a significant positive impact. As the output value of secondary and tertiary industries increases, the optimisation of industrial structure and technology further reduces carbon emission intensity. Technological innovation promotes low-carbon technology and industrial upgrading, reducing carbon emissions per unit of output. The optimisation of energy structure, especially the use of clean energy, further reduces carbon emissions. In the central region of Jilin Province, industrial structure, economic development level, urbanisation level, government behaviour, technological innovation level, and energy structure all have a significant positive effect, except for the significant negative effect of the factor of the level of opening up to the outside world. It indicates that import and export trade in the central region promotes technology transfer and the adoption of international standards, and reduces carbon emissions. However, the increase in the output value of the secondary and tertiary industries, the increase in per capita GDP, the growth of urban population, the increase in financial expenditure, the level of technological innovation, and the adjustment of the energy structure all increase the intensity of carbon emissions in the short term. The energy consumption of cities in the process of infrastructure construction and urban electricity consumption triggers a series of problems such as changes in land use and environmental pollution, which indirectly contributes to the convergence of urban carbon emission intensity to high values. This suggests that governments need to optimise industrial structure and financial expenditure, and strengthen the application of low-carbon technologies and clean energy in order to achieve sustainable development.

Table 4. Results of conditional β -convergence test of carbon emission intensity between Jilin Province and each region.

Variant	Jilin Province as a whole		Eastern part		Western Region		Central Region	
	OLS	SEM	OLS	SEM	OLS	SAR	OLS	SDM
β	- 0.976** * (-31.30)	- 0.979** * (-35.73)	- 0.462** * (-2.93)	- 0.985** * (-4.44)	- 0.547** * (-3.40)	- 0.532** * (-5.00)	- 0.827** * (-6.20)	- 1.162** * (-12.84)
p/λ	-	-0.255* (-1.70)	-	- 0.940** * (-8.79)	-	- 0.0535* (-0.89)	-	-0.325* (-1.85)
IS	0.779** * (6.43)	0.792** * (7.41)	0.412 (0.09)	-0.467 (-0.21)	0.104** (2.69)	0.105** * (4.15)	-0.950 (-0.04)	0.436** * (2.80)
PGDP	-	-	-0.168	-	0.538	-0.367	-0.543	0.354**

	0.137** * (-2.67)	0.144** * (-3.09)	(-1.15)	0.448** * (-3.84)	(0.04)	(-0.37)	(-0.60)	* (3.18)
UR	-0.282 (-0.26)	-0.228 (-0.25)	-0.179 (-1.00)	- 0.188** (-1.37)	-0.280 (-0.13)	-0.361 (-0.02)	-0.317 (-0.13)	0.434** (2.16)
GOV	0.321** * (6.32)	0.314** * (7.01)	0.211 (0.26)	0.118* (1.67)	0.231 (1.46)	0.203* (1.88)	0.732** * (3.59)	0.126** * (8.10)
PAT	0.482 (0.46)	0.627 (0.64)	-0.951** (-2.49)	-0.447* (-1.54)	-0.714*** (-2.93)	-0.701*** (-4.38)	0.662 (0.90)	0.865*** (5.50)
OPEN	-0.550 (-0.58)	-0.510 (-0.61)	-0.165 (-0.19)	- 0.125** (-2.06)	-0.679 (-0.86)	-0.507 (-0.92)	0.136 (0.06)	- 0.147** * (-4.96)
EI	-0.377* (-1.76)	- 0.376** (-2.01)	0.177 (0.71)	0.314 (0.21)	-0.585 (-0.53)	- 0.925** (-1.13)	0.564** (2.66)	0.147** * (7.17)
ν	0.049	0.049	0.025	0.046	0.051	0.038	0.040	0.051
R^2	0.963	0.869	0.760	0.149	0.993	0.978	0.898	0.413
N	135	135	45	45	45	45	45	45

Note: * * *, * * and * denote significance at the 1%, 5% and 10% levels, respectively, with *t*-statistics in parentheses and rates of convergence in %.

5. Conclusions

Under the goal of "double carbon", accelerating carbon emission reduction is an important part of promoting economic high-quality synergistic development in Jilin Province. This paper analyses the regional differences, σ -convergence and β -convergence characteristics of carbon emission intensity in each region of Jilin Province through *Dagum Gini coefficient* decomposition method, coefficient of variation and spatial panel data model, based on the carbon emission intensity level of Jilin Province from 2009 to 2023. The main research conclusions are as follows:

First, in the decomposition of regional differences, the Gini coefficients of carbon emission intensity in Jilin province and the regions show a more obvious imbalance, and the degree of this imbalance has increased in general. During the sample period, the average value of the overall *Gini coefficient* of carbon emission intensity in Jilin Province from 2009-2023 is 0.207, which contributes 45.83 per cent to the hypervariable intensity and is the main source of the overall differences. The inter-regional differences between the central and western regions of Jilin Province are the largest, with a mean *Gini coefficient* value of 0.256, followed by the eastern and western regions, and the eastern and central regions. The highest *Gini coefficient* value of carbon emission intensity within the group of central Jilin Province means that the phenomenon is most obvious among cities in the central region, followed by the western region, and then the eastern region.

Second, in terms of spatial convergence characteristics, Jilin Province as a whole has certain σ -convergence characteristics, and σ -convergence characteristics are not obvious in the eastern, western and central regions. There are different degrees of absolute β convergence of carbon emission intensity in Jilin province as a whole, western region and central region; conditional β convergence exists in Jilin province and all regions, and the speed of conditional β convergence is significantly faster than

that of absolute β convergence, and there are differences in the factors of carbon reduction effect in different regions, and there is a certain degree of spatial heterogeneity in the influence.

It provides a basis for the formulation of carbon emission reduction policies in Jilin Province, and guides the Jilin provincial government to consider carbon emissions when planning economic development and to enhance the level of environmental protection. Based on the findings of this paper, the following policy recommendations are obtained:

First, optimise the industrial structure. Jilin Province should increase support for clean energy and low-carbon technologies, and promote the transformation and upgrading of traditional high-carbon industries to low-carbon industries. At the same time, the development of emerging renewable energy industries is encouraged to reduce the carbon emission intensity in Jilin Province.

Second, strengthen energy conservation and management. By formulating stricter energy consumption standards and policies, enterprises and residents will be prompted to conserve energy and reduce carbon emissions. In addition, strengthen energy management and enhance energy utilisation efficiency to promote the green and sustainable development of energy consumption in Jilin Province.

Third, promote the greening of transport. Jilin Province should increase investment in public transport and non-motorised transport, improve the layout of the public transport network, encourage residents to reduce the use of cars, and promote green travel. In addition, the development and promotion of new energy transport should be increased to reduce the contribution of transport to carbon emissions and help the green transformation and sustainable development of the transport sector in Jilin Province.

In conclusion, the policy recommendations of this study will provide important references and guidance for Jilin Province in implementing carbon emission reduction policies and promoting sustainable development, and are expected to make positive contributions to carbon emission reduction in Jilin Province and other regions.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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