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Spatial spillover effects of carbon trading pilot policies on regional energy consumption structure optimization

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Abstract: Using panel data covering 30 provinces and cities in China between 2009 and 2019, this study provides an in-depth analysis of the spatial spillover effects of carbon trading pilot regions in promoting the optimization of energy consumption structure. Through the test of the spatial econometric model, it is found that the carbon trading pilot policy exhibits obvious spatial positive autocorrelation, which positively promotes the optimization of the energy consumption structure of the neighboring non-pilot regions. This positive impact also has a time lag characteristic, i.e., its effect on the optimization of the energy consumption structure of the neighboring regions gradually appears in the two years after the implementation of the policy. From a geographical perspective, the central region is the only region that shows a significant positive spillover effect.

Keywords: Carbon trading pilot policy; Energy consumption structure optimization; Spatial spillover effect.

1. Introduction

With the deepening connection between provinces and cities in China in terms of economic development, industrial structure adjustment and political system formulation, scholars have begun to analyze the interconnection of China's regional carbon trading pilot policies from the spatial dimension.

In the early stage of the implementation of carbon trading policy, some scholars [1] have explored the spatial agglomeration phenomenon of carbon emissions of the policy, and found that the invisible competition among enterprises selling carbon emission rights in the market transaction leads to the price of carbon emission rights to be constantly low, which triggers the concentration of regional carbon emissions, and in the long run, this phenomenon of agglomeration will pose a greater threat to the regional ecological environment. While Xue Ling and other scholars [2] constructed a spatial economic model to explore the dynamic impact between carbon emissions trading and enterprise location choice behavior, pointing out that the tendency of regional carbon policy will change the spatial layout of enterprises, which will help narrow the gap between regions. Scholar Mao Chunmiao et al [3] studied the spatial spillover effect of carbon trading policy on the level of high-quality development from the perspective of manufacturing industry, and found that the high-quality development of the manufacturing industry in the pilot region is not only affected by the local carbon trading policy, but also affected by the ripple effect of the implementation of carbon trading policy in other provinces and cities. Scholar Yu [4], on the other hand, explored the spatial spillover effect of carbon trading policy from the perspective of enterprise labor demand, and found that the policy has a positive spillover effect of about 10% on the employment market of enterprises in neighboring provinces and cities in the pilot region, and this positive effect is gradually increasing. Scholar Zhang [5] used the SCD model to study the spatial spillover effect of China's carbon market on renewable energy, and found that although the implementation of the carbon market inhibited the development of renewable energy in the pilot region, it promoted the development of renewable energy in the neighboring regions, and the spatial spillover effect outweighed the direct inhibition effect.

Since President Xi Jinping announced at the 75th United Nations General Assembly on September 22, 2020 that China would peak its carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, the issue of carbon emissions has been of great concern to academics. The research of Li Zhiguo and other scholars [6] shows that the carbon emissions trading mechanism has a significant policy spillover effect on carbon emissions, but the indirect effect only accounts for 27% of the total effect, indicating that the carbon trading policy has a poor channel in promoting the spatial spillover effect of emission reduction, and it still poses a threat of growth to carbon emissions in neighboring regions. The research of Guo Li et al [7] shows again that carbon emissions trading not only improves the local carbon emissions efficiency, but also has a positive role in promoting the carbon emissions efficiency of neighboring regions. Scholars Yang Jianping et al [8] similarly argued that the spatial spillover effect of the carbon trading pilot policy significantly inhibits carbon emissions in neighboring regions, and the long-term effect is more significant. Wuzheni et al [9] studied the spatial spillover effect of the carbon trading pilot policy from the perspective of carbon emissions transfer responsibility, and found that the implementation of the policy obviously prompted the pilot cities to transfer the implied carbon emissions responsibility to non-pilot cities. In addition, other scholars have proposed that the carbon emissions trading policy has a significant spatial spillover effect on energy utilization efficiency [10].

At present, most of the assessments on the optimization effect of carbon trading pilot policies on energy consumption structure focus on the pilot regions of the policies, and few studies consider the correlation of energy consumption structure between adjacent regions, especially the spatial spillover effect of environmental regulations on the surrounding areas. This may lead to biased policy assessment results. Therefore, this study will start from the spatial spillover effects of carbon trading pilot policies on energy consumption structure optimization, to provide more theoretical and empirical support for the study of carbon trading pilot policies and energy consumption structure.

2. Analysis of Spatial Autocorrelation Test Results

Waldo Tobler put forward the first law of geography in 1970, pointing out that geographic things or their attributes have certain spatial correlation. Some scholars have found after research that the optimization of energy consumption structure in various regions of China presents significant spatial autocorrelation. From the theoretical point of view, the carbon trading pilot policy has the same potential to promote the optimization of the energy consumption structure of neighboring regions. Under the current background of the country actively advocating the concept of green environmental protection and low carbon, the spatial correlation of energy consumption structure should become an important consideration in the formulation of low carbon policies in China.

2.1. Global Spatial Autocorrelation Test

In order to examine whether there is a global spatial correlation between energy consumption in 30 provinces and cities in China, the neighboring spatial weight matrix (W1) and the geographic distance weight matrix (W2) are used as the basis, respectively. In this paper, the spatial correlation between different provinces and cities is firstly examined by applying Moran's I index, which is the first step of the regression calculation of spatial modeling. The Moran's I statistic can be expressed as:

$$\mathrm{I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{i,j}\, z_i z_j}{S_0\sum_{i=1}^{n} z_i^2}$$

Where z_i is the deviation of the attribute of element i from its mean $(x_i - \bar{X})$, $\omega_{i,j}$ is the spatial weight between elements i and j, n is equal to the total number of elements, and S_0 is the aggregation of all spatial weights:

$$S_0 = \sum_{j=1}^{n}\sum_{j=1}^{n}\omega_{i,j}$$

The statistical z_I score is calculated in the following form:

$$z_I = \frac{I - E[I]}{\sqrt{V[I]}}$$

Among:

$$E[I] = -1/(n-1)$$

$$V[I] = E[I^2] - E[I]^2$$

The Moran index lies between (-1, 1), the larger the absolute value value indicates the stronger the correlation, when the value tends to 1, it indicates that there is a strong spatial positive correlation between the explained variables and the explanatory variables, if the value tends to 0, it indicates that there is no spatial correlation between the explained variables and the explanatory variables.

Able3-1 shows the results of the spatial autocorrelation test of energy consumption structure indicators for 30 provinces and cities in China under two different spatial weight matrices during the period from 2009 to 2019. Specifically, in the context of the spatial neighbor matrix (labeled W1), the global Moran indices of energy consumption structure lie in the range of 0.182 to 0.313, and these index values all show positive values at the 5% significance level. In contrast, in the context of the geographic distance weight matrix (labeled W2), the global Moran index lies in the range of 0.066 to 0.180, and most of the index values are significant at the 10% significance level. Together, these results indicate that there is a significant positive correlation between the energy consumption structures of the provinces and cities in China.

Table 1. Values of the Moran Index of Energy Consumption Structure Indicators, 2009-2019

Year	W1		W2	
	I	p-value*	I	p-value*
2009	0.236	0.015***	0.118	0.072*
2010	0.182	0.036**	0.066	0.159
2011	0.296	0.004***	0.133	0.055*
2012	0.313	0.003***	0.180	0.020**
2013	0.296	0.004***	0.156	0.034**
2014	0.286	0.005***	0.143	0.045**
2015	0.243	0.013**	0.104	0.091*
2016	0.261	0.009***	0.130	0.057*
2017	0.248	0.011**	0.109	0.084*
2018	0.264	0.008***	0.108	0.085*
2019	0.261	0.009***	0.105	0.090*

(Note: ***, **, * indicate that the variable is statistically significant at the 1%, 5%, and 10% levels, respectively)

2.2. Local Spatial Autocorrelation Test

In the analysis process, although the global Moran index can reveal the overall characteristics of the explanatory and interpreted variables, it may fail to adequately reflect the specific degree of spatial correlation among provinces and cities. To compensate for this limitation, the local Moran's index is used to detect outliers as well as the specific extent and location of the clustering of high and low values. In this paper, based on the spatial adjacency matrix (W1) and the geographic distance weight matrix (W2), local Moran scatter plots of the energy consumption structure of 30 provinces and cities in China in 2015 and 2018 are plotted to explore the spatial autocorrelation of each region in greater depth.

As shown in Figures1 and 2, whether in 2015 or 2018, the fitted regression line mostly crosses the first and third quadrants, presenting a clustered distribution of “high - high, low - low”. Specifically, the provinces and cities located in the first quadrant indicate that the degree of optimization of energy consumption structure indicators is high, and the degree of optimization of the surrounding areas is also relatively high; while the provinces and cities located in the third quadrant indicate that the degree of optimization of energy consumption structure indicators is low, and the degree of optimization of the surrounding areas is also relatively low. This distribution feature is clearly shown by the Moran scatter plot in the first and third quadrants, which further confirms the significant spatial agglomeration and positive autocorrelation of the optimization level of China's energy consumption structure.

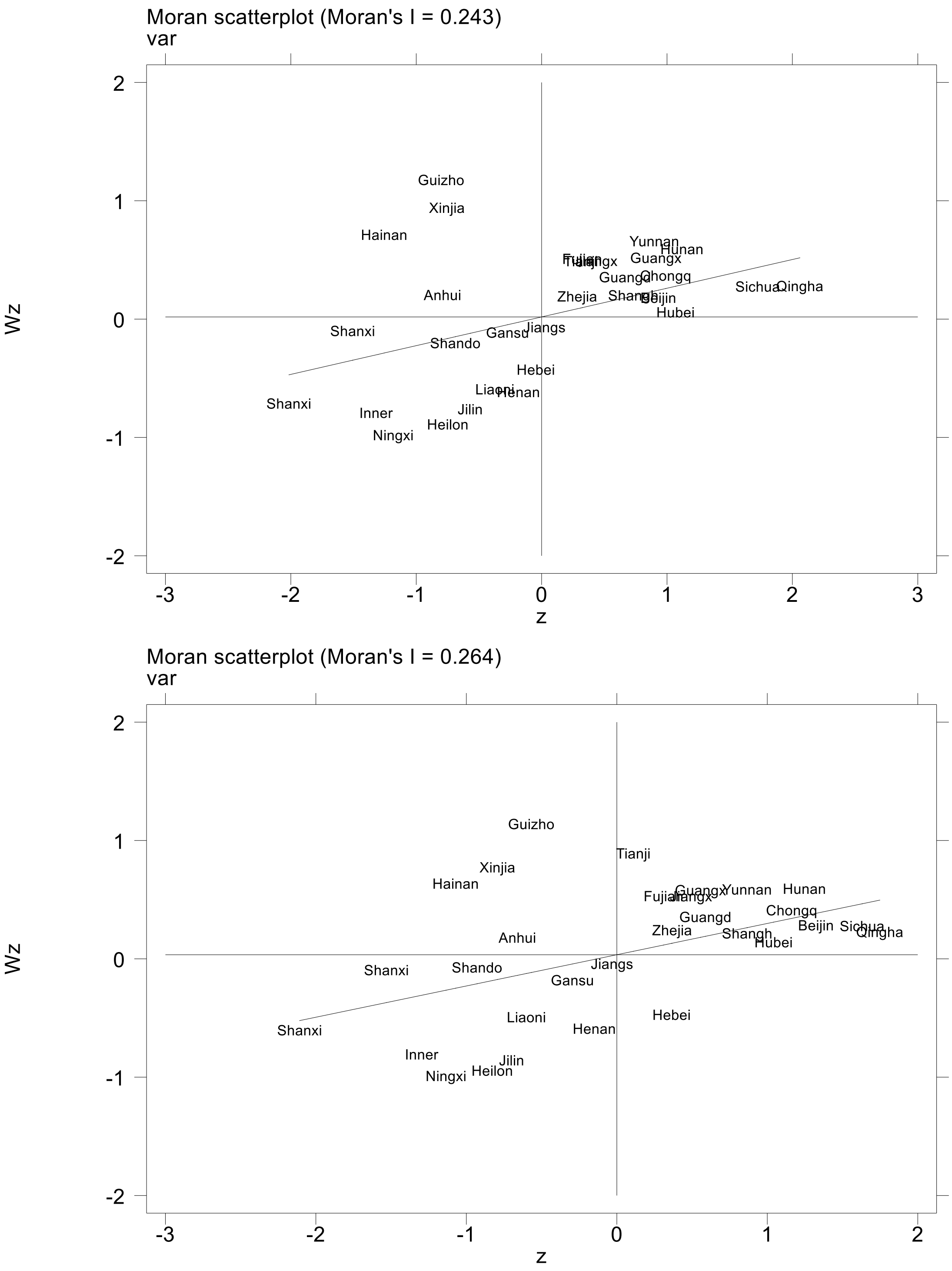

Figure 1. Moran Scatter Plot of Energy Consumption Structure Indicators for 2015 and 2018 based on the W1 Matrix under the

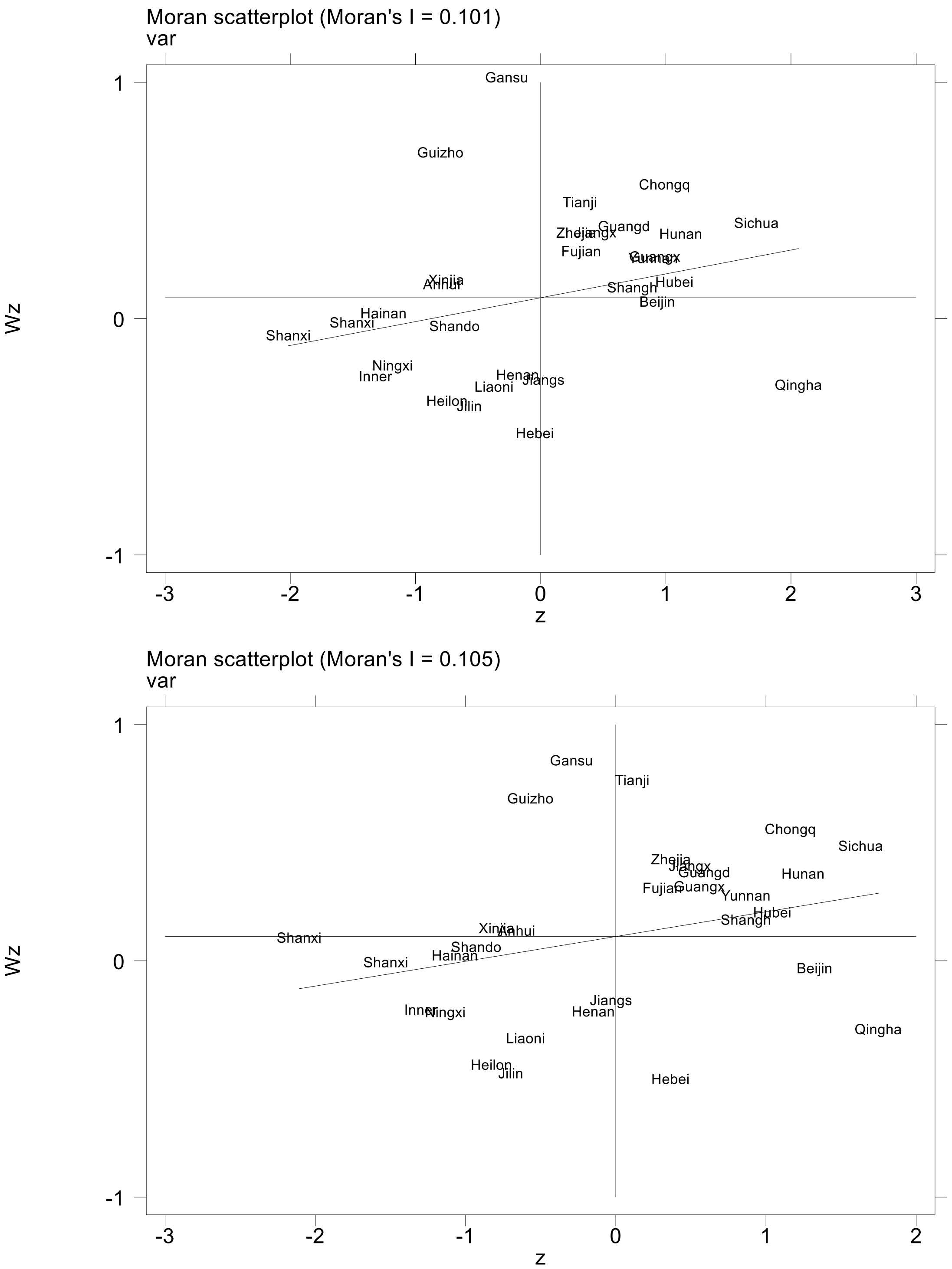

Figure 2. Moran Scatter Plot of Energy Consumption Structure Indicators for 2015 and 2018 based on the W2 Matrix under the

3. Spatial Econometric Model Construction

By analyzing the global and local Moran indices, we find that the carbon trading pilot policy and the energy consumption structure indicators exhibit significant spatial dependence at both the aggregate and local levels, which prompts us to consider constructing a spatial econometric model to test the spatial spillover effect between these two variables. Given the existence of three basic spatial econometric models to choose from, we adopt the LM test to determine the type of spatial relationship between carbon trading pilot policies and energy consumption structure optimization indicators.

The LM test bases its judgment on the results of LM-Log and LM-Error. When both are not significant, it indicates that there is no spatial relationship between the two variables, and an ordinary regression model should be used; if LM-Log is significant and LM-Error is not, a spatial lag model (SLM) is more appropriate; on the contrary, if LM-Log is not significant and LM-Error is significant, then a spatial error model (SEM) should be chosen; and if both are significant, then a further Wald and LR tests to make a decision.

In this paper, two matrices, W1 and W2, were utilized and the LM test results in Table 2 were referred to. The results show that the coefficients of LM-error, Robust LM-lag, and LM-error of the energy consumption structure optimization index are all positive, and their P-values are less than 0.05, passing the 5% significance test. This indicates that the spatial effect of the carbon trading pilot policy on the optimization of energy consumption structure contains both the spatial error effect and the lag effect, so we choose the spatial Durbin model (SDM) as the optimal spatial measurement model.

Table 2. LM test results

Test		LM-lag	Robust LM-lag	LM-error	Robust LM-error
energy consumption structure	W1	53.821*** (0.000)	6.537** (0.011)	108.213*** (0.000)	60.929*** (0.000)
	W2	85.647***	30.281***	56.456***	1.090
		(0.000)	(0.000)	(0.000)	(0.296)

To ensure the robustness and exact selection of the model, we further employ the Wald and LR tests to verify whether the spatial Durbin model (SDM) reduces to a spatial error model or a spatial autoregressive model. Specifically, if the Wald-lag test result is not significant, it indicates that the SDM can be reduced to a spatial autoregressive model; if the Wald-error test result is not significant, it implies that the SDM can be reduced to a spatial error model; similarly, if the LR-SDM-SEM test result is not significant, the SDM will be reduced to a spatial error model; if the LR-SDM-SAR test is not significant, the SDM will reduce to a spatial autoregressive model.

We conducted Wald and LR tests using both W1 and W2 matrices and summarized the results in Table 3. In the context of the W1 matrix, the coefficients of Wald-lag, Wald-error, LR-SDM-SEM, and LR-SDM-SAR are all significant at the 1% significance level, which means that we rejected the original hypothesis, i.e., the SDM model is not degraded, and passed the robustness test.

Table 3. Wald, LR test results

Test		Wald-lag	Wald-error	LR-SDM-SEM	LR-SDM-SAR
Energy consumption structure	W1	40.60*** (0.0000)	44.30*** (0.0000)	41.68*** (0.0000)	38.48*** (0.0000)
	W2	64.66*** (0.0000)	55.52*** (0.0000)	52.53*** (0.0000)	60.68*** (0.0000)

4. Analysis of Spatial Econometric Model Results

Before the model estimation, it is also necessary to carry out the Hausman test to determine whether the model applies fixed effects or random effects. According to Table 4, it can be seen that the Hausman statistic of the index of the degree of optimization of energy consumption structure under the two spatial matrices is 33.76 and 34.16, with a P-value of 0.0000, which is less than 0.01, and the test result is significant at the 1% level, i.e., the original hypothesis of the random effect model is rejected, and a fixed effect model is chosen to do the subsequent empirical analysis.

Table 4. Space Hausman test results

VARIABLES	W1	W2
Chi2 statistic	33.76***	34.16***
P	(0.0000)	(0.0000)
Observations	330	330
self-selection effect	fixed effect	fixed effect

4.1. Spatial Spillover Analysis of The Effect of Carbon Trading Pilot Policy on Optimizing Regional Energy Consumption Structure

In this paper, the level of industrialization (INL), the share of industrial value added in GDP is used. For government intervention (GC), the share of local general budget expenditures in GDP is selected. The level of external development (O) is measured by the amount of regional foreign-invested enterprise investment, which is converted to RMB using the current year's exchange rate, and is characterized by its share of regional GDP. The level of economic development (GDP), expressed in logarithmic terms as per capita GDP at constant 2008 prices. The level of urbanization (U) is the share of urban population in the total population of both regions.

Tables 5 and 6 show the regression results of spatial econometric models for the indicators of the degree of optimization of energy consumption structure in detail, while Tables 7-5 and 7-6 present the estimation results of the four models, SEM (spatial error model), SAR (spatial autoregressive model), SDM (spatial Durbin model), and dynamic SDM, respectively, under the neighboring spatial weighting matrix (W1) and the geographic distance weighting matrix (W2). Results. Comparing the data in these tables, we can derive the following analysis:

The coefficients of the dummy variable policytreat are all significantly positive at the 1% statistical level in the SEM, SAR and SDM models, but in the dynamic SDM model, the coefficient is significantly negative at the 1% level. This indicates that the carbon trading pilot policy has played a significant role in promoting the optimization of energy consumption structure in pilot provinces and cities, while the spillover effect on adjacent non-pilot provinces and cities has a certain lag. However, in general, the policy still has a certain positive impact on the optimization of energy consumption structure in adjacent non-pilot provinces and cities. This may be since the pilot regions have fulfilled their emission reduction tasks by adjusting their resource consumption structure and other measures, which has brought pressure and challenges to the neighboring non-pilot regions, and at the same time provided experience and reference, prompting the neighboring regions to take corresponding measures to optimize their resource consumption structure and thus reduce GHG emissions.

Table 5. Estimation results of SEM, SAR, SDM and dynamic SDM for energy consumption structure under W1

Variable	SEM	SAR	SDM		Dynamic state SDM	
	Main	Main	Main	Wx	Main	Wx
L. policytreat					0.8173*** (4.68)	
policytreat	0.0068*** (3.46)	0.0067*** (3.48)	0.0068*** (3.54)	0.0102** (2.55)	0.0131*** (3.47)	-0.0128* (-1.76)
Gdp	0.0011 (0.75)	0.0010 (0.68)	-0.0008 (-0.54)	-0.0011 (-0.43)	0.0064** (2.30)	0.0028 (0.61)
O	-0.0003* (-1.94)	-0.0003* (-1.93)	-0.0004** (-2.38)	-0.0009** (-2.31)	0.0003** (2.18)	0.0002 (0.63)
U	-0.0454*** (-2.70)	-0.0455*** (-2.73)	-0.0414** (-2.51)	0.0331 (0.88)	-0.0360*** (-5.56)	0.04328** (2.49)
Gc	-0.0406** (-2.43)	-0.0429*** (-2.57)	-0.0463*** (-2.77)	-0.0189 (-0.58)	-0.0098 (-0.62)	-0.0540 (-1.45)
Inl	0.0342*** (3.16)	0.0326*** (3.36)	0.0164* (1.65)	0.0969*** (5.73)	-0.0039 (-1.46)	-0.0228*** (-2.84)
lambda	0.08 (0.86)	0.1579** (2.02)	0.09 (1.12)		0.0314 (0.31)	
sigma2	0.0001*** (12.83)	0.0001*** (12.8)	0.0001*** (12.83)		0.0001*** (13.47)	
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	330	330	330	330	330	330
R-squared	0.7263	0.7349	0.7197		0.6255	

Table 6. Estimation results of SEM, SAR, SDM and dynamic SDM of energy consumption structure under W2

Variable	SEM	SAR	SDM		Dynamic state SDM	
	Main	Main	Main	Wx	Main	Wx
L. policytreat					-0.4956*** (-3.29)	
policytreat	0.0089*** (4.61)	0.0073*** (3.79)	0.0072*** (3.95)	0.0148*** (3.18)	0.0076*** (4.04)	0.0173*** (3.61)
Gdp	0.0011 (0.71)	0.0008 (0.54)	0.0020 (1.40)	0.0005 (0.16)	0.0010 (0.74)	-0.0000 (-0.01)
O	-0.0004*** (-2.76)	-0.0004** (-2.38)	-0.0004*** (-2.68)	-0.0006 (-1.31)	-0.0004*** (-2.85)	-0.0009* (-1.68)
U	-0.0534*** (-3.23)	-0.0457*** (-2.71)	-0.0346** (-2.21)	-0.3255*** (-6.68)	-0.0374** (-2.24)	-0.3343*** (-6.59)
Gc	-0.0543*** (-3.11)	-0.0421** (-2.51)	-0.0549*** (-3.43)	-0.0916*** (-2.64)	-0.0639*** (-3.78)	-0.1262*** (-3.39)
inl	0.0501*** (5.41)	0.0396*** (4.11)	0.0295*** (3.03)	0.0293*** (2.73)	0.0400*** (3.49)	0.0412*** (3.21)
lambda	0.3254*** (-2.96)	-0.024 (-0.25)	-0.2562** (-2.52)		0.1423(1.25)	
sigma2	0.0001*** (12.68)	0.0001*** (12.87)	0.0001*** (12.69)		0.0001*** (13.4)	
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	330	330	330	330	330	330
R-squared	0.7258	0.7233	0.7870		0.7467	

Observing the regression results of other control variables on the indicators of the degree of optimization of energy consumption structure, we can find that, on the one hand, the urbanization level, the degree of government intervention and the level of opening up to the outside world of the pilot regions have negative spatial spillover effects on the optimization of the energy consumption structure of non-pilot regions. Specifically, the higher level of urbanization, the stronger degree of government intervention, and the higher level of opening up to the outside world in the pilot regions may inhibit the optimization of energy consumption structure in the surrounding non-pilot regions. This may be due to the fact that the urbanization process in the pilot provinces and cities intensifies the demand for energy resources and creates resource competition with neighboring regions; the spillover effects of government policies may lead to difficulties in policy implementation in neighboring regions; and the effects of technology introduction and diffusion brought about by opening up to the outside world may be limited by the absorption capacity and innovation capacity in neighboring regions. On the other hand, the industrialization level of the pilot regions has a significant positive spillover effect on the optimization of the energy consumption structure of the non-pilot regions. As the industrialization level of the pilot regions increases, their industrial chain extends to the surrounding non-pilot regions, promoting the optimization and upgrading of the industrial structure in the adjacent regions, and thus promoting the optimization of the energy consumption structure.

In summary, the carbon trading pilot policy has an impact on the optimization of the energy consumption structure in both the pilot and adjacent non-pilot regions, but there are differences in the way and extent of the impact. Meanwhile, other control variables also have significant spatial spillover effects on the optimization of energy consumption structure.

In order to more clearly articulate the specific impact of the dummy variables in the pilot regions on the neighboring non-pilot regions, we need to consider the direct and spatial spillover effects of the dummy variables on the explanatory variables in an integrated manner. Therefore, we further decompose the effects of policy implementation on the explanatory variables. Among them, the direct effect measures the direct impact of the carbon trading pilot policy on the optimization of energy consumption structure in the pilot regions; the indirect effect reveals the facilitating effect of the carbon trading pilot policy on the optimization of energy consumption structure in the non-pilot regions through the spatial spillover mechanism; and the total effect integrally reflects the overall impact of the carbon trading pilot policy on all provinces and municipalities in terms of optimization of energy consumption structure.

Table 7 shows in detail the impacts of the direct, indirect and total effects of the carbon trading pilot policy on the optimization of energy consumption structure under the two matrix frameworks of W1 and W2. By analyzing the table, the following conclusion can be drawn: at the 1% statistical significance level, the direct, indirect and total effects of carbon trading policies on the optimization of energy consumption structure are all significantly positive. This means that the carbon trading pilot policy not only positively promotes the optimization of energy consumption structure in all regions, but also positively promotes the optimization of energy consumption structure in the surrounding neighboring regions through spatial spillover effects.

Table 7. Effect decomposition of the impact of carbon trading pilot policy on energy consumption structure

Test		LR_Direct	LR_Indirect	LR_Total
energy consumption structure	W1	0.0071*** (3.62)	0.0116*** (2.65)	0.0187*** (3.79)
	W2	0.0067*** (3.52)	0.0106*** (2.65)	0.0173*** (4.38)

4.2. Analysis of Spatial Spillover Effect Regression Results Based on Regional Heterogeneity

In order to deeply study the spatial effects of the impact of carbon trading pilot policies on the optimization of energy consumption structure in different regions, this paper conducted a spatial econometric model test based on the neighboring spatial weight matrix (W1) and geographic distance weight matrix (W2), using the spatial Durbin model with time and individual double fixed effects for samples in the eastern, central and western regions during the period of 2009-2019, and the regression results are detailed in Tables 8.

From the regional level, there are significant differences in the impact of carbon trading pilot policies on the optimization of energy consumption structure. Specifically, the regression coefficients of the dummy variables in the central region are significantly positive at the 1% level, indicating that the carbon trading pilot policy in the central region effectively promotes the optimization of energy consumption structure in the region. In contrast, the regression coefficients of the dummy variables in the eastern and western regions do not pass the significance test, indicating that the carbon trading pilot policies in these regions do not have a significant direct impact on the optimization of energy consumption structure. In the test results of the spatial econometric model under the W1 matrix, the coefficient of the dummy variable in the western region is negative, while it turns positive under the W2 matrix, which may be due to the influence of different spatial weight matrices on the direction and intensity of the spatial spillover effect.

In order to further analyze the relationship between the spatial effects of the carbon trading pilot policy on the optimization of the energy consumption structure in the region and adjacent regions, the direct and indirect effects of the variables under the SDM model are decomposed and tested in Tables 9. The results show that the carbon trading pilot policy in the central region has a significant positive effect on the optimization of its own energy consumption structure (the coefficient is 0.0165, significant at the 1% level), and has a significant positive spillover effect on the optimization of the energy consumption structure in the neighboring regions of the region (significant at the 5% level). However, neither the direct nor indirect effects are significant for the eastern and western regions.

For the eastern region, although its industry, energy restructuring and economic development are in a leading position, providing a good economic environment and institutional foundation for the implementation of the carbon trading pilot policy, the direct effect of the carbon trading pilot policy on the optimization of energy consumption structure is not obvious under the existing energy consumption constraints as well as the policy conditions because the existing energy consumption structure is already close to the optimal state. At the same time, the indirect effect of the policy on the optimization of the energy consumption structure of the neighboring non-pilot provinces and cities is also not significant enough.

In contrast, in the western region, due to the relatively single industrial structure, the dominant industries are energy- or resource-consuming traditional industries with high energy consumption, high pollution, and low efficiency, and the level of economic development is relatively low, and the research and development and application of clean energy and low-carbon technologies are also relatively lagging. Therefore, the effect of the carbon trading pilot policy on the optimization of the energy consumption structure in the western region is not significant, and the pilot provinces and cities have not been able to better drive the adjustment and optimization of the energy consumption structure of the neighboring non-pilot provinces and cities.

Table 8. Model regression results of SDM with spatial effect based on regional heterogeneity

	W1			W2		
	East	Middle	West	East	Middle	West
policytreat	0.0014 (0.63)	0.0202*** (6.34)	-0.0032 (-0.63)	0.0012 (0.55)	0.0223*** (5.43)	0.003 (0.56)
lambda	-0.1893* (-1.70)	-0.3819*** (-3.58)	-0.362** (-2.30)	-0.2658** (-2.04)	-0.3817*** (-2.64)	-0.2828** (-2.50)
sigma2	0.0001*** (7.68)	0.0000*** (6.30)	0.0001*** (7.59)	0.0001*** (7.70)	0.0001*** (6.69)	0.0001*** (7.71)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	121	88	121	121	88	121
R-squared	0.5631	0.8123	0.6754	0.0693	0.8278	0.7801

Table 9. Spatial Durbin model regression decomposition results based on regional heterogeneity

	East		Middle		West	
	LR_Direct	LR_Indirect	LR_Direct	LR_Indirect	LR_Direct	LR_Indirect
W1	0.0013 (0.57)	0.0022 (0.64)	0.0165*** (5.70)	0.0171** (2.36)	-0.0010 (-0.21)	-0.0195 (-1.33)
W2	0.0011 (0.47)	0.0026 (0.64)	0.0186*** (5.20)	0.0229** (2.51)	0.0032 (0.61)	0.0001 (0.00)

5. Main Findings and Recommendations for Countermeasures

5.1. Main Research Conclusions

Based on referring to and sorting out many domestic and international literature, this paper explores the spatial spillover effect of the carbon trading pilot policy by using spatial econometric modeling based on the panel data of 30 provinces and municipalities (except Tibet) in China from 2009 to 2019. The main conclusions are as follows: through the spatial econometric model test, it is found that the carbon trading pilot policy has spatial positive autocorrelation on the optimization of the energy consumption structure in the region, which is characterized by the spatial distribution of "high-high, low-low", and at the same time, it has a significant role in promoting the optimization of the energy consumption structure of the neighboring non-pilot regions. From the national level, the carbon trading pilot policy has a positive spatial spillover effect, and from the sub-regional perspective, only the carbon trading pilot policy in the central region has a significant positive spillover effect on the energy consumption structure of the neighboring non-pilot regions.

5.2. Countermeasure Suggestions

Based on the optimization impact and spatial spillover effect of carbon trading pilot policy on energy consumption structure, this paper puts forward the following suggestions:

Strengthen the implementation of carbon trading policy in the central region. Given that the carbon trading pilot policy in the central region has a significant positive impact on the optimization of energy consumption structure, it is recommended to further increase the implementation of the policy in the region, and to promote the continuous optimization of energy consumption structure by means of perfecting the market mechanism, strengthening regulation and incentives.

Explore the new path of carbon trading policy in the eastern region. Although the direct impact of the carbon trading pilot policy in the eastern region is not significant, its economic environment and institutional foundation are good. Therefore, it is recommended to explore new policy paths suitable for the characteristics of the eastern region, such as combining industrial upgrading, technological innovation and green transformation strategies to seek new breakthroughs in optimizing the energy consumption structure.

Increase policy support and guidance for the western region. Due to the single industrial structure and relatively low level of economic development in the western region, the impact of the carbon trading pilot policy on the optimization of its energy consumption structure is limited. Therefore, it is recommended to increase policy support and guidance for the western region, and through financial support, technical assistance and talent cultivation measures, help it to enhance the R&D and application capacity of clean energy and low-carbon technologies, and promote the transformation and upgrading of the energy consumption structure.

Strengthen inter-regional policy coordination and cooperation. Considering the spatial spillover effect of carbon trading pilot policies, it is recommended to strengthen inter-regional policy coordination and cooperation, establish cross-regional policy synergy mechanisms, and jointly promote the optimization and upgrading of energy consumption structure. Maximize the effect of the policies through information sharing, experience exchange and joint actions.

Improve the construction and supervision of the carbon trading market. In order to give full play to the role of carbon trading policies in the optimization of energy consumption structure, it is recommended to further improve the construction and supervision mechanism of the carbon trading market. This includes strengthening the construction of market infrastructure, enhancing market transparency, strengthening supervision and risk prevention, etc., to ensure the healthy and orderly development of the carbon trading market.

Promote the diversification of energy consumption structure. In the process of optimizing the energy consumption structure, attention should be paid to promoting the diversified development of energy consumption. Through the development of renewable energy, improving energy utilization efficiency, promoting clean energy and other ways, reduce the degree of dependence on traditional energy sources, and improve the stability and sustainability of the energy consumption structure.

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