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Low Carbon Trade Efficiency and Trade Potential of Thailand and its Land Neighbors Based on Spatial Weight Gravity SLM Model

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Abstract— This study examines the low-carbon trade efficiency and trade potential among Thailand and its land neighbors–Myanmar, Laos, Cambodia, and Malaysia–using a Spatial Lag Model (SLM) and spatial weight matrix. The results indicate that Thailand serves as the regional trade hub with the highest low-carbon trade efficiency but limited growth potential. Myanmar exhibits significant trade potential due to its underdeveloped market, while Laos demonstrates strong spatial effects that could enhance trade growth. Malaysia shows weaker trade spillover effects, requiring policy-driven regional cooperation. Cambodia’s low-carbon trade efficiency remains low, necessitating industrial restructuring. Moran’s I analysis suggests weak spatial autocorrelation, indicating that low-carbon trade distribution is more influenced by economic policies than geographic proximity. To enhance regional low-carbon trade, nations should optimize infrastructure, strengthen policy coordination, and promote green supply chains.

Keywords: Low-carbon trade; Spatial Lag Model; Trade efficiency; Trade potential; Spatial weight matrix

I. INTRODUCTION

With the advancement of global carbon neutrality goals, low-carbon trade efficiency has become an important indicator for measuring the quality of trade among countries. Thailand and its land neighbors Myanmar, Laos, Cambodia, and Malaysia are jointly influenced by geographical factors, economic development level, industrial structure, and environmental policies in their trade exchanges. Therefore, studying the low-carbon trade efficiency and trade potential among these countries can help optimize the regional low-carbon trade pattern and improve the level of green economy cooperation (Gupta et al., 2019; Abdullahi et al., 2022).

The Spatial Weight Matrix (W) is used to describe spatial units, and its core is to define the spatial dependencies between each region and other regions, generally represented by W, where W ij represents the weight between region i and region j. Common construction methods include distance weighting based on geographic distance, adjacency weighting where two regions are adjacent and assigned a value of 1, otherwise assigned a value of 0, economic weighting, and comprehensive weighting that combine multiple factors to weight the construction. （Fally, 2015; Egger & Staub, 2016）。

The spatial weight matrix of this study is based on Thailand and its neighboring countries on land, including Cambodia, Laos, Malaysia, Myanmar, and Thailand, and constructs the low-carbon economic spatial relationship between countries based on the distance between the centroid points of the top three economic cities/regions in each country. This matrix is a symmetric matrix, where the elements represent the average distance between the centroids of major economic cities/regions between two countries, reflecting the degree of spatial correlation between them (Nguyen, 2022; Wahyudi&Anggita, 2015).

The traditional gravity model can explain bilateral trade flows well, but it fails to fully consider the spatial spillover effects of trade relations. Therefore, using the Spatial Lag Model (SLM) can more accurately evaluate trade efficiency and trade potential, revealing the spatial dependence of trade links between neighboring countries (Prehn et al., 2016; Ravishankar&Stack, 2014).

The Spatially Weighted Gravity Model is an extended version of the classical gravity model that introduces spatial weights. It is mainly used to analyze the interactive relationships between cities and regions in terms of economy, trade, and population flow. This model is derived from Newton's law of gravity, which states that the interaction force between two regions is proportional to their economic size and inversely proportional to spatial distance (Egger&Staub, 2016; Fally, 2015).

This thesis studies the bilateral low-carbon trade volume between Thailand and its neighboring countries, and combines the centroid of the top three economic cities in each country as the distance point for each country. A spatial weight matrix is constructed to analyze the SLM gravity model, and a low-carbon trade network between Thailand and neighboring countries is constructed to analyze trade, distance, and development prospects (Fan et al., 2016; Atif et al., 2017).

II.METHODOLOGY

2.1Spatial Lag Model(SLM)

The Spatial Lag Model is an important spatial econometric model mainly used to study the mutual influence of dependent variables in space. In this study, the trade gravity coefficient was used to analyze the interactions between regions. It is directly proportional to the trade volume between two countries and inversely proportional to the distance (Fally, 2015; Egger&Staub, 2016). After introducing the spatial weight matrix, the general form of the gravity model is:

$$T_{ij} = G\frac{M_i M_j}{d_{ij}^{\alpha}} W X_{ij} \epsilon_{ij} \quad (1)$$

Then, taking the logarithm of the spatial weight gravity model form mentioned above, the spatial weight SLM model can be obtained as the main model equation:

$$\ln T_{ij} = \rho W lnT_{ij} + \beta_1 lnGDP_i + \beta_2 lnGDP_j - \beta_3 lnd_{ij} + \beta_4 lnX_{ij} + \epsilon_{ij} \quad (2)$$

Among them,T_{ij}: indicate the low-carbon trade coefficient between region i and j; $M_i M_j$: the trade flow between the two countries; ρ : spatial autoregressive coefficient, measuring the spatial dependence of trade; W: the spatial weight matrix measures the spatial correlation between region i and region j; GDP_i, GDP_j: the economic scale of the two countries (derived fromM_i, M_j) (Prehn, Br ü mmer& Glauben, 2016); d_{ij}: the distance between two places i and j; X_{ij}: Other factors affecting trade, such as carbon dioxide emission intensity, etc. α: is the distance attenuation coefficient, usually greater than 1; ϵ_{ij}: Error term.

2.2 Spatial Weight Matrix

The spatial weight matrix (W) is mainly used to describe the interrelationships between regions in geographic space, especially in spatial econometrics, for modeling spatial dependencies. For the analysis of low-carbon economy in Thailand and neighboring countries on land, a distance based weight matrix can be used (Gupta et al., 2019).

In the setting of the spatial weight matrix W, this study uses the top three economic cities or regions in Myanmar, Thailand, and neighboring countries on land. After determining the coordinates using latitude and longitude, the distance centers of the three cities are calculated as the geographic coordinates of each country to calculate the economic and trade distance between Thailand and its neighboring countries on land, forming a spatial weight matrix. At the same time, in the selection of spatial coefficients, distance weights are chosen based on the reciprocal of the distance between neighboring countries (Ravishankar&Stack, 2014).

2.3 Moran Index:

Moran's I is a statistical indicator for measuring spatial autocorrelation, particularly suitable for analyzing whether a variable exhibits clustering effects in space (Fan et al., 2016). The Moran's I index is usually between [-1,1]: I>0 indicates positive spatial autocorrelation, and the data exhibits clustering effects, with high values clustered together and low values clustered together. I ≈0 indicates no spatial autocorrelation, variable values are randomly distributed in space, and there is no significant clustering effect. I < 0, Indicating negative spatial autocorrelation, with alternating high and low values, presenting a crossroads style.

2.4 Low Carbon Trade Efficiency Measurement

Low carbon trade efficiency is usually measured using the ratio of carbon emission intensity to trade flow or data envelopment analysis methods (Nguyen, 2022):

$$E_{ij} = \frac{T_{ij}}{C_{ij}} \quad (3)$$

Among them, E_{ij} is the low-carbon trade efficiency of the two countries, T_{ij} is the low-carbon trade volume of the two countries, C_{ij} is the carbon dioxide emissions of the two countries. By using the non radial directional distance function (DEA-SBM) to measure the total factor low-carbon trade efficiency, the efficiency levels between different countries were obtained and combined with SLM results for analysis (Abdullahi et al., 2022).

2.5 Trade Potential:

Trade potential refers to the difference between the theoretical maximum trade volume and the actual trade volume between a country and its neighboring countries. Calculating trade potential based on SLM model prediction of trade volume (Atif, Haiyun,&Mahmood, 2017):

$$P_{ij} = \frac{\hat{T}_{ij} - T_{ij}}{\hat{T}_{ij}} \quad (4)$$

Among them, P_{ij} is the low-carbon trade potential of the two countries, T_{ij} is the low-carbon trade volume of the two countries, $\hat{T}_{ij}$ is the predicted value of low-carbon trade between the two countries. If P_{ij}>0, it indicates that the country still has room for trade growth; If P_{ij}<0, it indicates that the country's trade has exceeded expectations, and there may be trade barriers or structural imbalances.

III.DATA SOURCES

The construction of the spatial weight matrix is based on the distance indicators between major cities in Thailand and neighboring countries, which are sourced from Wikipedia. The low-carbon economic trade volume, population, and GDP indicators of Thailand and neighboring countries are sourced from publicly available indicators from the World Bank. The carbon dioxide emissions data for Thailand and neighboring countries are sourced from publicly available data from 'Our Wold In Data'. The Moran's I index, trade efficiency, and trade potential indicators are derived from the author's calculations. The low-carbon trade volume between the two countries, as introduced in World Bank data, mainly involves the following types of products and practices: renewable energy technologies and equipment, energy-saving products and technologies, low-carbon transportation vehicles, sustainable agriculture and livestock products, green building materials, carbon capture and storage technology products, etc. (Wahyudi&Anggita, 2015).

IV. EMPIRICAL ANALYSIS

4.1 Spatial weight matrix SLM gravity model analysis of low-carbon trade

4.1.1 Spatial weight matrix and variable description

This spatial weight matrix constructs the spatial relationship of low-carbon economy based on the average distance between the centers of gravity of core cities in each country's economy.

Table1: Spatial Weight Matrix Distance Between Countries(in kilometers)

Countries	Cambodia	Laos	Malaysia	Myanmar	Thailand
Cambodia	0	649.9585	948.2505	1170.7581	574.2139
Laos	649.9585	0	1559.2333	837.4863	445.2687
Malaysia	948.2505	1559.2333	0	1737.4189	1279.208
Myanmar	1170.7581	837.4863	1737.4189	0	597.3234
Thailand	574.2139	445.2687	1279.208	597.3234	0

Source: Author's Calculation

The shorter distances (<600 km): Thailand Laos, Cambodia, Myanmar, may have higher spatial dependence, meaning that if Thailand's low-carbon policies, technological innovation, or investment expansion occur, their impact is more likely to be transmitted to these countries. Medium distance (600-1000 km): There may be some low-carbon economic interactions between Cambodia Laos and Malaysia Cambodia, but the impact is not as strong as that of short distance countries. Long distance (>1000 km): Due to the long distance between Malaysia and other countries, low-carbon economic cooperation may rely more on policy agreements, trade exchanges, or regional economic cooperation such as RCEP.

Table2: Descriptive statistical table of variables

Variable	n	Mean	SD	Median	Min	Max	Skew	Kurtosis
lctrade(dollar)	20	160166300	363985700	22726670	172800	1216363000	2.4	4.11
gdpto(dollar)	20	2.07922E+11	2.12899E+11	66757620000	15843160000	5.14969E+11	0.45	-1.76
distance(km)	20	979.91	430.71	892.87	445.27	1737.42	0.44	-1.27
co2to(ton)	20	125684100	126719000	30233220	20178440	288823700	0.39	-1.92

Source: Author's Calculation

Thailand is a core hub, and its low-carbon economic development has a significant impact on neighboring countries; Countries that are closer are more susceptible to the spatial diffusion of Thailand's low-carbon economy; Malaysia may rely more on policy cooperation due to its distance and weak low-carbon economic ties. This matrix provides a quantitative basis for analyzing the spatial spillover effects, policy synergies, and regional cooperation mechanisms of low-carbon economy.

4.1.2 SLM Gravity Model for Low Carbon Trade

The relationship between Thailand's GDP and trade is the strongest, with high spatial dependence. Trade has reached a high level, and potential growth space is limited. Malaysia's low-carbon trade efficiency is relatively low, and its trade spillover effects with neighboring countries are weak, resulting in limited growth potential. Myanmar's GDP has a significant impact on low-carbon trade, but the market has not been fully developed and still has development potential. The GDP of Laos has a significant promoting effect on trade, with significant spatial effects, and regional cooperation can further drive growth. Currently, Cambodia's low-carbon trade efficiency is poor and its correlation with economic variables is weak, indicating that there is still significant room for market growth.

Table3:SLM Gravity Model between Thailand and Four Land Neighboring Countries

Countries	Intercept	log(gdpto)	log(co2to)	log(populations)	Rho	sigma squared	AIC	LM Test (p-value)
Vietnam	0.85443 (9.5593)	1.66151 (4.4499)	-0.365 (3.9832)	-1.14912 (2.3964)	-0.0591	0.56425 (0.75117)	23.333	5.568 (0.0183)
Laos	-13.34967 (1.7433)	3.1618 (1.0393)	0.17292 (0.8696)	-3.78692 (0.6940)	0.8549	0.20042 (0.4477)	20.499	4.3921 (0.0361)
Malaysia	2.75827 (11.5696)	0.73836 (2.6323)	1.0772 (2.6762)	-1.20421 (1.4040)	-0.1604	0.17637 (0.41996)	17.545	6.5323 (0.0106)
Myanmar	-8.9393 (4.7375)	6.2828 (3.3304)	-3.1093 (2.1821)	-5.0058 (2.9065)	0.566	1.1742 (1.0836)	27.621	2.38 (0.1229)
Thailand	-13.39569 (5.0877)	1.35442 (0.1187)	0.18106 (0.0598)	-1.07743 (0.0969)	0.7202	0.01012 (0.1006)	4.4706	3.7916 (0.0515)

Source: Author's Calculation

From the above table, Cambodia's low-carbon trade efficiency is poor, and the correlation between trade and economic factors is weak. The role of GDP in promoting trade is relatively weak, and the impact of carbon emissions on trade is not significant. Population has a negative impact on trade, indicating that the size of the labor force has not effectively promoted low-carbon trade. The spatial effect (Rho) is close to zero, indicating that there is no significant spatial correlation between trade and neighboring countries' trade. Laos has a high low-carbon trade efficiency, and GDP has a strong promoting effect on trade. The strong impact of GDP on low-carbon trade indicates that economic growth can effectively drive low-carbon trade. The significant but negative impact of population on trade may reflect that the demographic dividend has not been fully realized. The spatial effect is significant (Rho=0.8549), indicating close trade relations with neighboring countries and significant spatial spillover effects. Malaysia's low-carbon trade efficiency is relatively low, and the impact of the economy and carbon emissions on trade is not significant. The weak impact of GDP and carbon emissions on trade indicates that economic development does not have a strong driving force for low-carbon trade. The weak spatial effect (Rho=-0.16038) indicates that Malaysia's low-carbon trade links with neighboring countries are relatively loose. Myanmar's low-carbon trade efficiency is relatively low, with a significant impact on GDP but strong volatility. GDP has a significant impact on trade, but carbon emissions have a weaker impact on trade. The spatial effect is moderate (Rho=0.56598), indicating a certain degree of spatial dependence in trade, but overall performance is unstable. Thailand has the highest low-carbon trade efficiency, and its GDP and carbon emissions have a significant impact on trade. GDP has a strong positive impact on low-carbon trade, indicating that economic growth directly promotes the development of low-carbon trade. Carbon emissions have a positive impact on trade, which may indicate that the green transformation of low-carbon trade is underway. The strong spatial effect (Rho=0.72017) indicates that Thailand's low-carbon trade is greatly influenced by neighboring countries, and the regional cooperation effect is obvious.

In the overall equation results, Thailand should consolidate regional cooperation and enhance its competitiveness in green trade. Continue to deepen regional integration cooperation, such as mechanisms like RCEP, and enhance the regional synergy of low-carbon trade. Promote the construction of clean energy and green supply chains, and improve the quality of low-carbon trade. Laos can strengthen the linkage between economic growth and green trade. Based on the growth momentum of GDP, optimize the trade structure, and attract more investment in low-carbon industries. Utilize spatial effects, strengthen cooperation with neighboring countries, and enhance the potential for trade growth. Meanwhile, Myanmar can improve its infrastructure and enhance trade stability. Focus on developing cross-border transportation infrastructure and improving low-carbon trade efficiency. Strengthen the guidance of green economy policies and attract investment from low-carbon enterprises. Malaysia's low-carbon trade, enhancing regional linkage, and increasing trade dependence. Due to low spatial dependence, low-carbon trade links with neighboring countries can be strengthened through regional policies. Promote innovative models such as digital trade and green finance, and improve the level of low-carbon trade. For Cambodia, enhance industrial structure and improve low-carbon trade efficiency. The efficiency of carbon trade is relatively low, and it is necessary to optimize the industrial structure and attract more investment in green manufacturing. Strengthen environmental policies, cooperate with neighboring countries, and enhance green trade capabilities. Overall, Thailand and Laos have performed well in low-carbon trade, Myanmar and Cambodia still have great potential, and Malaysia needs to strengthen regional cooperation to improve low-carbon trade efficiency.

4.2 Moran's I Residual Analysis

Moran's I analysis of low-carbon trade can evaluate the existence of regional trade effects by analyzing the spatial autocorrelation of low-carbon trade in various countries. Here are the Moran'I indices for each country:

Table4: Moran's I statistical results of residuals

Model	Moran I Statistic	Expectation	Variance	Standard Deviate	p-value
Cambodia	-0.22064	-0.25	0.006332	0.36896	0.3561
Laos	-0.2671	-0.25	0.006296	-0.21547	0.5853
Malaysia	-0.15706	-0.25	0.006286	1.1723	0.1205
Myanmar	-0.1643	-0.25	0.006315	1.0784	0.1404
Thailand	-0.23736	-0.25	0.006267	0.15962	0.4366

Source: Author's Calculation

Based on the Moran's I results of all countries, the spatial autocorrelation is weak or non-existent. The Moran's I values of all models and countries are low and the p-value is large, indicating that there is no significant autocorrelation between low-carbon trade and model residuals in space. These results indicate that both low-carbon trade and model residuals in the analysis did not exhibit strong spatial clustering effects. In other words, the distribution or residual of low-carbon trade does not have a clear geographical agglomeration pattern, but rather shows a relatively uniform distribution, which may mean that the influencing factors of low-carbon trade are dispersed and not strongly influenced by geographical proximity.

4.3 Analysis of Low Carbon Trade Efficiency and Trade Potential

Based on residual data, the low-carbon trade efficiency of Thailand and each landlocked country can be analyzed. The residual represents the difference between the actual trade level and the model's predicted value, with smaller residuals typically indicating higher trade efficiency. From the perspective of low-carbon trade potential, based on the predicted values of the above model, we can analyze the low-carbon trade potential of each country from the strength, fluctuation, and trend of the predicted values. The following table shows the low-carbon trade efficiency and trade potential of each country.

Table5:Low Carbon Trade Efficiency& Potential in 5 Countries

Countries	Trade Efficiency	Trade Potential
Cambodia	-0.122722	29.452188
Laos	-0.4340936	22.394557
Malaysia	-0.333224	33.1630628
Myanmar	-0.0477642	21.962952

Thailand	0.9378042	41.2495348

Source: Author's Calculation

In terms of efficiency index, Thailand, a highly efficient country, has a relatively high low-carbon trade efficiency with small fluctuations and stable performance. The residual value is close to 0, indicating that its actual trade level is close to the model prediction. Myanmar, an inefficient country, has significant fluctuations in its low-carbon trade efficiency, large residual differences, and unstable and poor performance. Medium efficiency countries, represented by Laos and Malaysia, have relatively moderate performance, with Laos fluctuating less and Malaysia fluctuating more, but overall efficiency is lower. Cambodia is a country with high volatility, with significant fluctuations in residual values. Although it sometimes performs well, overall it has low efficiency and high volatility. Thailand has shown the most stable and good performance in low-carbon trade efficiency, while Laos and Malaysia have moderate low-carbon trade efficiency, and Myanmar and Cambodia have low and fluctuating efficiency.

According to the trade potential table, Thailand shows the most stable and good performance in low-carbon trade potential, with relatively small fluctuations in potential and a relatively balanced overall level. Although Myanmar has great potential, it is highly volatile, while Laos and Malaysia have significant potential fluctuations, occasionally showing lower potential. Cambodia, on the other hand, shows weaker performance with fluctuating potential, fluctuating from high to low. Despite fluctuations, Myanmar, a high potential country, has a relatively high low-carbon trade potential overall, especially in certain periods where the potential value is significantly higher than other countries. Middle to high potential countries include Laos and Malaysia, both of which have significant fluctuations in their potential performance. Although their potential performance is strong in some periods, there is also significant instability, especially in Laos where negative values occasionally occur. Thailand is a country with stable potential, and its low-carbon trade potential is relatively stable, with balanced performance and small fluctuations. The overall potential is in the range of moderate to high. Although Cambodia has high potential in some periods, overall, its low-carbon trade potential fluctuates greatly and performs weakly in some periods.

V. CONCLUSION

This study analyzes the low-carbon trade efficiency and trade potential between Thailand and its land neighbors Myanmar, Laos, Cambodia, and Malaysia based on spatial weight matrix and spatial lag model (SLM). Research has found that geographical distance, economic development level, industrial structure, and environmental policies have significant impacts on low-carbon trade efficiency.

Firstly, Thailand is at the core of the low-carbon trade network, benefiting from strong trade dependence and economic scale. Its low-carbon trade efficiency is the highest and trade stability is strong. However, Thailand's trade growth potential is limited, and in the future, efforts should be made to improve trade quality by deepening regional cooperation and promoting the construction of green supply chains. Under the promotion of regional cooperation, Laos has relatively high low-carbon trade efficiency and has certain growth potential. Due to the underdeveloped market, Myanmar's GDP plays a significant role in promoting trade, indicating that there is still considerable room for development in its low-carbon trade. However, the country has low trade stability and needs to improve infrastructure to enhance trade efficiency. Although Malaysia has a good economic foundation, the spatial spillover effects of low-carbon trade are relatively weak, and its trade links with neighboring countries are relatively loose. In the future, it needs to enhance regional trade linkage through policy cooperation. Cambodia's low-carbon trade efficiency is relatively low, and its correlation with economic variables is weak. The industrial structure still needs to be optimized to enhance its green trade capabilities.

The Moran's I index analysis shows that the spatial autocorrelation of low-carbon trade is weak, and the distribution of trade efficiency is relatively uniform, indicating that geographical proximity has limited impact on low-carbon trade and is more influenced by economic policies and market factors. In addition, the calculation results of low-carbon trade efficiency show that Thailand has the highest trade efficiency, while Myanmar and Cambodia have lower and more volatile efficiency, while Laos and Malaysia are at a moderate level. The analysis of trade potential shows that Myanmar has the highest potential for trade growth, while Laos and Malaysia have some fluctuations, Thailand has stable performance, and Cambodia's trade potential is limited.

Overall, Thailand should continue to promote regional green trade cooperation, Laos can use its economic growth momentum to optimize its trade structure, Myanmar needs to improve its infrastructure to enhance trade stability, Malaysia should strengthen regional linkage, and Cambodia needs to adjust its industrial structure to improve low-carbon trade efficiency.

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