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Impact of the Belt and Road Initiative on Economic-Social-Natural Ecological Niches and Their Coupling Coordination: Evidence From 11 Countries Along the Route

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The Belt and Road Initiative (BRI) significantly contributes to the world economy. However, the central part of the Belt and Road (B&R) is located in fragile ecological zones that are arid, semi-arid, or sub-humid. Using the entropy method, the economic-social-natural ecological niches and their coupling coordination during 2007–2019 along B&R's 11 countries were explored along with regional differences and spatiotemporal characteristics. The economic-social-natural ecological niches were low, with a fluctuating upward trend. Additionally, the average annual growth rate of the synthesis ecological niche dramatically improved after the BRI. Further, the BRI facilitated inter-country trade and promoted the economic ecological niche. However, the BRI marginally affected the social ecological position, possibly because the social ecological niche was high pre-BRI. The natural ecological niche showed a negative growth after the BRI. Further, the coupling coordination of economic-social ecological niche and natural ecological niche showed an upward trend, transforming from severe discoordination to advanced coordination. Although BRI promoted advanced coordination, it did not affect internal categories. Policy recommendations for sustainable development in China-ASEAN Free Trade Area were provided. This study can assist policymakers to balance economic-social development and environmental protection.

Keywords: BRI, complex ecosystem, coupling coordination, ecological niche, CAFTA-DR

1 INTRODUCTION

Since the second half of the 20th century, continuous population expansion and rapid economic growth have accelerated both the consumption of natural resources and environmental issues worldwide, further challenging sustainable development (Janjua et al., 2021; Arbolino et al., 2022). To address these problems, international organizations agreed to strengthen international cooperation. The Paris Agreement aims to limit the increase in global average temperature to less than 2°C compared to the pre-industrial period and strive to limit the global temperature increase to less than 1.5°C (Tost et al., 2020). In 2013, China proposed to jointly build the Silk Road Economic Belt and the 21st Century Maritime Silk Road, also known as the "Belt and Road Initiative (BRI)". It aimed to strengthen mutually beneficial cooperation among countries along the designated route, promote stable regional development, and provide public goods globally (Qi et al., 2019).

The areas of countries in the central part of B&R have expanded to include 39% of the global land area, 31% of the global gross domestic product (GDP), 24% of the global household consumption, and 62% of the global population (Liu et al., 2020). Acting as a promising platform for international collaboration, it has attracted increasing global attention from governments, academics, and businesses worldwide (Laurance William and Arrea Irene, 2017; Ascensão et al., 2018). However, although the emerging countries concentrated in the region receive shared benefits, they face global environmental issues (Saud et al., 2020). According to the World Bank (2020), the GDP of the 57 BRI countries accounted for 32.55% of the total global GDP in 2019, and their carbon emissions from fossil fuel combustion increased from 38.65% in 2000 to 57.06% in 2018, which are likely to increase further as their economies develop. China, having the highest carbon emissions in B&R, had an average annual increase rate of carbon emissions of 5.34% during 1971–2018, which was higher than the average annual increase rate of carbon emissions worldwide (Lu et al., 2020; Yang et al., 2022). With such environmental issues prevailing, attention should be given to the coordinated economic-social-natural development of the BRI (Grecu et al., 2018; Yao et al., 2020; Debnath et al., 2021; Retallack, 2021), and not only its trade and economic development (Huang, 2016; Olander et al., 2018; Chen et al., 2020; Carlucci et al., 2021; Alves and Lee, 2022). However, such a holistic study that can summarize the economic, social, ecological, and environmental issues has still not been well documented.

The BRI should be studied on a large-scale and not just locally; that is, all associated subsystems should be studied. However, the heterogeneity in variables selected for the system and the lack of a uniform indicator make such studies difficult. Therefore, subsystems have often been studied separately (Guinan et al., 2009; Sillero, 2011; Gelviz-Gelvez et al., 2015; Bajocco et al., 2016). Fortunately, the concept of ecological niche provides a unified measurement unit for each subsystem (Rosas et al., 2019; de Andrade et al., 2020). The term "ecological niche" was first coined by Johnson in 1910, who defined it as "different species in the same area can occupy different ecological niches in the environment" (Grinnell, 1917). In 1957, Hutchinson defined an ecological niche as a multidimensional ecological factor space wherein individual organisms or species live freely (Odum, 1983). Unlike natural ecosystems, complex ecosystems are dominated by human activities and comprise several natural, social, and economic subsystems, that are interdependent on and complementary to each other (Castellanos et al., 2019; Chaloner et al., 2020). Because of its vast and complex internal structure, an ecological approach was proposed to study complex economic-social-natural ecosystems, and to explore practical methods of promoting both sustainable cities and human well-being (Chen et al., 2007; Feng et al., 2019). Ecological niches within complex systems can also measure the degree of interaction between the natural environment and human activities and assess the sustainability of complex economic-social-natural systems within the study area (Funk et al., 2013; Casanelles-Abella et al., 2021).

While studying complex ecosystems, the natural subsystem provides a social subsystem with material conditions for secondary processing. The processed products are regulated and distributed through the economic subsystem's production, consumption, and circulation chains to provide economic benefits. The economic benefits are introduced back to the social and natural subsystems by regulating social resources and improving natural conditions, thus, promoting continuous improvements in the territory of the inhabitants, enhancing the quality of life and living standards, and ultimately achieving human well-being. The social and economic subsystems are essential for the rational and efficient use of natural resources and for improving the living standards of urban and rural residents. Accordingly, we define economic and social ecological niches as the respective level of social services and economic conditions that economic and social subsystems can provide, or can be used by inhabitants in a complex ecosystem (Wang et al., 2011). A high economic and social ecological niche provides a better living environment for the inhabitants. Moreover, studying the economic and social ecological niches requires rational and efficient regulation and distribution of natural resources, and the establishment of a solid scientific basis to achieve sustainable development and human well-being (**Figure 1**).

In addition to unifying subsystem measurement units for complex systems, coupling coordination has attracted research attention (Cui et al., 2019; Cai et al., 2021). If complex ecosystem subsystems are not coordinated, problems, such as irrational allocation of resources, incompatible land use and economic-social systems, and natural environment destruction, which affect the development of the ecological niche system, arise. Changes in any one subsystem will cause changes in the internal economic, social, and natural ecological niche systems; therefore, the regulations of such changes in complex ecosystems can be assessed by constructing economic-social-natural indicators (Pan et al., 2019; Wang et al., 2021). Accordingly, a comprehensive indicator system for complex ecosystems based on the coupling coordination degree model has been built to quantitatively analyse the relationship between economic-social development and natural resources.

Despite the importance of BRI worldwide, countries along its route are predominantly located in arid, semi-arid, or sub-humid fragile ecosystems (Ng et al., 2020), that are both sensitive and show weak self-recovery (Chen et al., 2016; Hughes et al., 2020; Li et al., 2021). Additionally, these ecosystems exhibit regional differences in resource and environmental conditions, such as unevenly distributed water resources (Fang et al., 2021), zonal gradients in soil and vegetation elements (Skokanová et al., 2020; Oiry and Barillé, 2021), and uneven production and consumption (Huang, 2019; Hussain et al., 2020). Consequently, these areas will most likely face several environmental challenges due to global climate change and increased human activity, which may cause negative economic-social and ecological impacts on the ecosystem. For example, severe smog from polluting industries in East Asia has caused widespread public concern and respiratory diseases (He et al., 2017; Akinyemi and Mashame, 2018; Gu et al., 2018). Further, the development of trade and transport networks may increase the risk of biological invasion (Liu et al., 2019), and infrastructure development may cause significant environmental impacts, consequently, exacerbating human footprints and damaging ecosystems (Weng et al., 2021).

In this study, we examined the spatiotemporal changes in the degree of coordinated coupling of complex systems in 11 B&R countries since BRI implementation, using the entropy method and concept map of complex ecosystems. We described economic-social-natural complex ecosystems to assess the development status of the subsystem ecological niche as part of its assessment framework and performed a spatiotemporal analysis of the impacts of the BRI. The following research questions were discussed: 1) What is a complex ecosystem? 2) How is it measured? 3) Does BRI affect subsystems?

The paper has been organised as follows: First, the research background, status, and the concept of economic-social-natural complex ecosystems have been presented. Second, research methods, index selection method, and data sources have been described. Third, the statistical results have been presented, followed by the discussion of the results. Finally, the key findings and policy suggestions have been summarized in the conclusion. The results of this study provide a reference for exploring the impacts of the BRI, and advance the understanding of sustainable development.

2 MATERIALS AND METHODS

2.1 Study Area

The China-ASEAN Free Trade Area (CAFTA) plays a pivotal role in B&R construction (Filipski et al., 2011). It will be a free trade area having the highest population globally. Further, it will rank third globally in the economic scale after the European Union and North American Free Trade Agreement, and will represent the largest free trade area formed by developing countries. Geographically, CAFTA countries are located adjacent to Asia. Economic globalization and regional economic integration have not only prompted the World Trade Organization member countries to establish free trade relations with other relevant countries, but also triggered the development of CAFTA (Kose and Rebucci, 2005). According to The Human Development Report 2019, four CAFTA countries (Brunei, Thailand, Singapore, and China) rank globally in the top 100 countries in terms of the human development index, thus, demonstrating their remarkable success in human social development. However, as trade cooperation strengthens, environmental problems are increasing. Ecological security is the foundation for sustainable development. Regarding ecological balance, measuring the ecological niche of CAFTA's social-economic-natural complex ecosystems can promote the sustainable development of the CAFTA countries and provide international experience to advance high-quality B&R construction (Cheng, 2016; Jiang et al., 2021) (**Figure 2**).

2.2 Niche Assessment in Complex Ecosystem

An indicator system to evaluate ecological niches in a complex ecosystem comprises indicators that meet certain principles, such as scientific validity, feasibility, independence, completeness, simplicity, hierarchy, and stability (Kusters et al., 2020).

Drawing on prior research and considering the complexity of ecosystem and the accessibility of indicators, a total of 29 indicators were selected across the three dimensions (economy, society, nature) to construct the indicator system for complex ecosystem (**Table 1**). The economic ecological niche includes the level of economic development, economic structure, and economic strength (Shi et al., 2021; Tisdell and Seidl, 2004). Economic development represents the size and rate of a country's economic development and includes three indicators. Economic structure comprises national economy and measures the efficient use of human, material, financial, and natural resources. Economic strength refers to a country's influence on the global economy and includes three indicators (**Table 1**). The social ecological niche includes both the quality of life and science and technology (Bardsley and Bardsley, 2014), with seven indicators used to measure the quality of life (**Table 1**). Due to data availability, two representative categories were selected to measure science and technology. The natural ecological niche represents an integrated measure of how much biologically productive land and water is required to produce the proportion of resources consumed and to absorb the waste generated by corresponding human activities; thus, it includes both environmental protection and resource security (Rees, 1992). Natural ecosystem degradation, environmental quality deterioration, and adverse environmental effects caused by human activities represent environmental problems (Funk et al., 2013; Leidenberger et al., 2015; Kumar et al., 2017; Zou et al., 2021). Compared with other studies (Wang et al., 2011; Hong et al., 2016; Tai et al., 2020), this paper considered people's quality of life in the selection of social ecological niche indicators. With the development and progress of society, people begin to pay more and more attention to the convenience and comfort of the living environment.

2.3 Data Collection

Data of 11 B&R countries (Vietnam, Laos, Cambodia, Myanmar, Thailand, Singapore, Malaysia, Indonesia, Philippines, Brunei, and China) for 2007–2019 were collected from the World Bank data (https://www.worldbank.org/en/home) to illustrate the post-BRI impact. China first presented the BRI in 2013, and thus, data were divided into two groups: 1) 6 years before BRI and 2) 6 years after BRI, to compare the development impacts in countries along the route. Using the available data from the World Bank, the missing data were interpolated by linear interpolation method. The boundaries of administrative regions and national locations were obtained from the 1:4,000,000 database of the national basic geographic information center and the standard map service website of the State Bureau of surveying, mapping, and geographic information (http://bzdt.nasg.gov.cn/); the downloaded drawing number is GS (2016) 2,885 standard map production.

TABLE 1 | Constructed indicator system for assessing ecological niches in complex ecosystems is shown in the table. The "+" refers to positive indicators, and the "–" refers to negative indicators. As explained in the paper, positive and negative indicators are treated differently when normalizing the data.

Object Layer	Sub-system	Guideline Layer	Layer	Attribute
Synthesis ecological niche	Economic ecological niche	Economic development	GDP per capita	+
			GDP per capita growth	+
			Unemployment rate	–
		Economic structure	Manufacturing value added of GDP	+
			Services value added of GDP	+
			Population ages 65 and above	–
		Economic strength	Final consumption expenditure per capital	+
			Bop balance	–
			Net foreign direct investment	+
	Social ecological niche	Quality of life	Primary school enrollment	+
			Life expectancy	+
			Domestic general government health expenditure	+
			People using basic sanitation services	+
			Neonatal mortality rate	–
			Mobile phone subscriptions	+
			Individuals using the Internet	+
			Access to electricity	+
		Science and technology	Medium and high-tech exports	+
			Scientific and technical journal articles	+
	Natural ecological niche	Environmental protection	Forest area	+
			CO_2 emissions	–
			PM2.5 air pollution	–
			Threatened species	–
		Resource security	Natural resources depletion	–
			Mineral depletion	–
			Arable land per capita	+
			Crop production index	+
			Renewable energy consumption	+
			Electricity consumption	–

2.4 Methodologies

2.4.1 Entropy Method

The entropy method is an objective assignment method used to determine the dispersion degree of an indicator. In this study, first, the data were normalized by determining the positive indicators (**Eq. 1**) and negative indicators (**Eq. 2**) described in **Table 1**.

$$x'_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \tag{1}$$

$$x'_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \tag{2}$$

Second, the weight of the indicator value of the ith evaluation object under the jth indicator was calculated as follows:

$$P_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}} \tag{3}$$

Third, the entropy of the jth indicator was calculated using the degree of information redundancy d_j.

$$e_j = -k\sum_{j=1}^{m} p_{ij} ln(p_{ij}), d_j = 1 - e_j \tag{4}$$

Where: $k = \frac{1}{\ln m} \geq 0$, and if $P_{ij} = 0$, then the definition is $\lim_{P_{ij} \to 0} P_{ij}\, ln(P_{ij}) = 0$.

Finally, the weighting of indicators was determined as follows:

$$w_j = \frac{d_j}{\sum_{i=1}^{n} d_j} \tag{5}$$

2.4.2 Regional Variation Measurement

The coefficient of variation (CV), Gini coefficient (G), and Thiel's index (T), all of which indicate the overall differences in the level of ecological niches in the complex ecosystem of the CAFTA countries, were calculated as follows:

$$\text{CV} = \frac{\sqrt{\sum_{i=1}^{n} (z_i - \bar{z})^2 / n}}{\bar{z}} \tag{6}$$

$$\text{G} = \frac{2}{\bar{z}n^2} (z_1 + 2z_2 + 3z_3 + \ldots + Nz_n) - \frac{n+1}{n} \tag{7}$$

$$\text{T} = \frac{1}{n} \sum_{i=1}^{n} \frac{z_i}{\bar{z}} ln \frac{z_i}{\bar{z}} \tag{8}$$

Where Z_i is the combined assessed value of the ecological niche of the economic-social-natural complex ecosystem calculated by the entropy method, Z_i indicates the combined estimated value of the ith country, and $\bar{Z}$ represents the average value.

TABLE 2 | Classification of the stages of coupling coordination of economic-social-natural complex ecosystems.

System Layer	Rule Layer (D Range)	Category Layer (Comparison of P_1 and P_2)	Symbol
Coordinated development	Advanced coordination $(0.8 < D \le 1)$	Natural ecological niche lag $(P_1 - P_2 > 0.05)$	I1
		Economic-social ecological niche lag $(P_2 - P_1 > 0.05)$	I2
		System balance $0 \le \lvert P_1 - P_2 \rvert \le 0.05$	I3
	Basic coordination $(0.5 < D \le 0.8)$	Natural ecological niche lag $(P_1 - P_2 > 0.05)$	II1
		Economic-social ecological niche lag $(P_2 - P_1 > 0.05)$	II2
		System balance $0 \le \lvert P_1 - P_2 \rvert \le 0.05$	II3
Uncoordinated development	Basic discoordination $(0.3 < D \le 0.5)$	Natural ecological niche lag $(P_1 - P_2 > 0.05)$	III1
		Economic-social ecological niche lag $(P_2 - P_1 > 0.05)$	III2
		System balance $0 \le \lvert P_1 - P_2 \rvert \le 0.05$	III3
	Severe discoordination $(0 < D \le 0.3)$	Natural ecological niche lag $(P_1 - P_2 > 0.05)$	IV1
		Economic-social ecological niche lag $(P_2 - P_1 > 0.05)$	IV2
		System balance $0 \le \lvert P_1 - P_2 \rvert \le 0.05$	IV3

2.4.3 Coupling Coordination Measures

The coupling coordination model can analyse the degree to which elements are interrelated and influence each other and the development of the parameters in the same system. The economic-social ecological niche and the natural ecological niche are independent and interrelated sub-system features of a complex ecosystem. Their coupling degree was calculated as follows:

$$C = \left[\frac{U_1 + U_2}{(U_1 + U_2)^2} \right]^{1/2} \tag{9}$$

where coupling C falls in the interval $[0, 1]$, and U_1 and U_2 represent the average economic-social and natural ecological niches, respectively. Coupling coordination was further refined based on the coupling degree to measure the developmental degree of the level of coupled coordination between subsystems. It was calculated as follows:

$$T = \alpha U_1 + \beta U_2 \tag{10}$$

$$D = \sqrt{C * T} \tag{11}$$

The interval of the coupling coordination D value belonged to the interval [0,1]. As the contributions of the economic-social and natural ecological niches to the comprehensive evaluation of ecological niches in the complex ecosystem can be compared, the coefficients (α and β) to be determined were assumed to be 0.5. We classified coupling coordination into four broad categories and 12 subcategories (**Table 2**).

2.5 Data Analysis

The data were analysed using MATLAB_R2015b and SPSS 24.0 statistical software. Specifically, MATLAB_R2015b was used to standardize the data and assign weights to the indicators derived by the entropy method, and SPSS 24.0 statistical software was used to measure the CV, G, and T values, and determine the coupled coordination of the economic-social and natural ecological niches.

3 RESULTS

3.1 Changes in the Economic-Social-Natural Ecological Niche of the China-ASEAN Free Trade Area Countries

Overall, the economic-social-natural ecological niche of the CAFTA countries showed a fluctuating upward trend from 2007 to 2019. Specifically, during 2007–2012, the average value of synthesis ecological niche in CAFTA countries was 0.3534, and during 2014–2019, it was 0.3928, which was higher than the pre-BRI values. The average economic ecological niche values before and after the BRI were 0.3232 and 0.3450, respectively. The social ecological niche had the highest index values among the three subsystems during 2007–2012 (0.4147) and 2014–2019 (0.5081). The natural ecological niche of the CAFTA countries during 2007–2019 changed marginally, with its value being the lowest in the subsystem before BRI (0.3222) and after the BRI (0.3254).

The spatial distribution of complex ecosystems in the CAFTA countries before and after the BRI is shown in **Figure 3**. The economic-social-natural complex ecological niches were high in the areas southeast of the CAFTA countries. Before the BRI (2007 and 2010), the complex ecosystem index was significantly higher in China than in other regions. High index values were mainly concentrated in all equatorial countries, except China. Laos had the lowest complex ecosystem index in 2007, but it increased in 2010, whereas Cambodia had the lowest complex ecosystem index in 2010 with no changes in the value in 2013 compared to the 2010 value. Subsequently, Cambodia's complex ecosystem index increased significantly from 0.1797 to 0.184.

In 2016, the complex ecosystem index decreased particularly in China and Laos. The index remained essentially unchanged in other countries, such as Vietnam, Cambodia, Myanmar, and Singapore. Notably, China's complex ecosystem index before the BRI was surprisingly higher than that after the BRI. In 2019, the complex ecosystem index rebounded. For example,

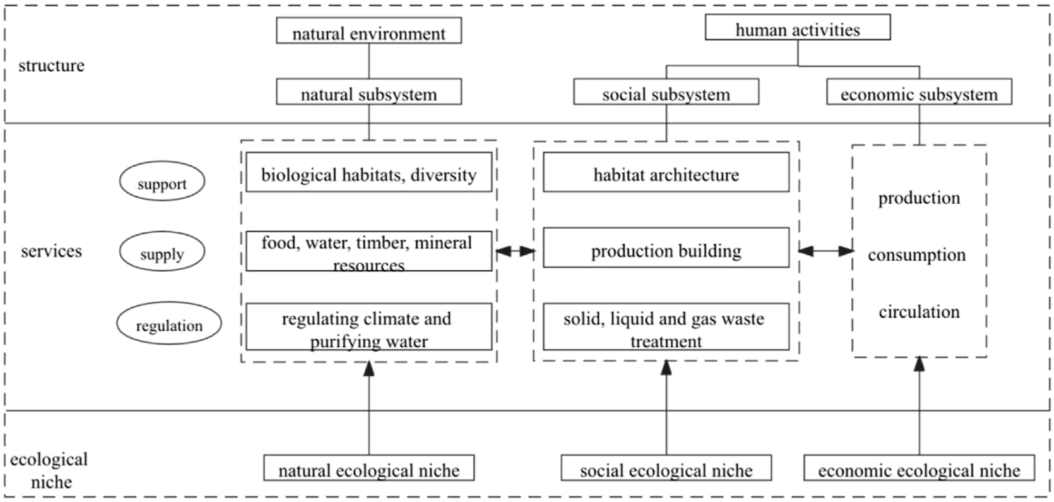

FIGURE 1 | Concept map of complex ecosystems.

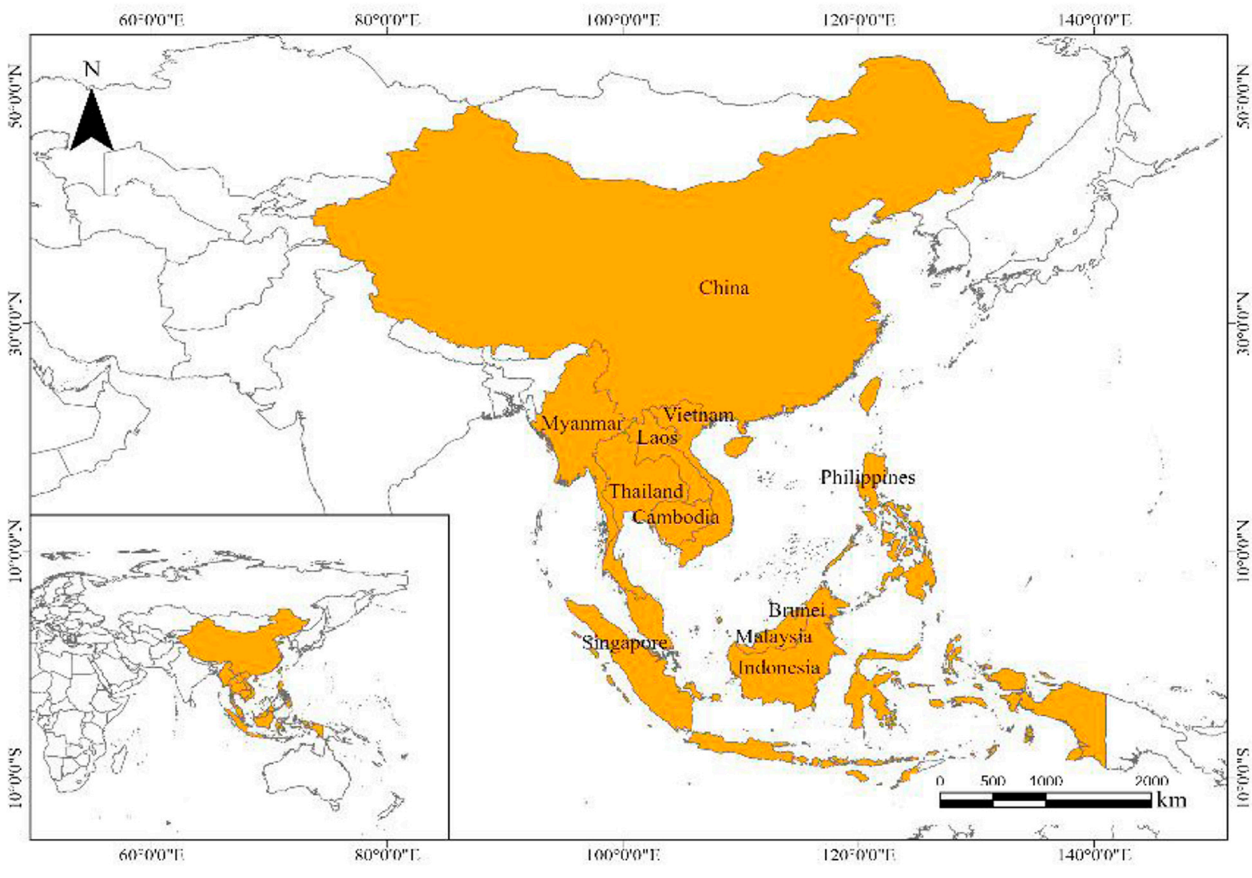

FIGURE 2 | Geographical location of the study area and the 11 countries along the B&R route.

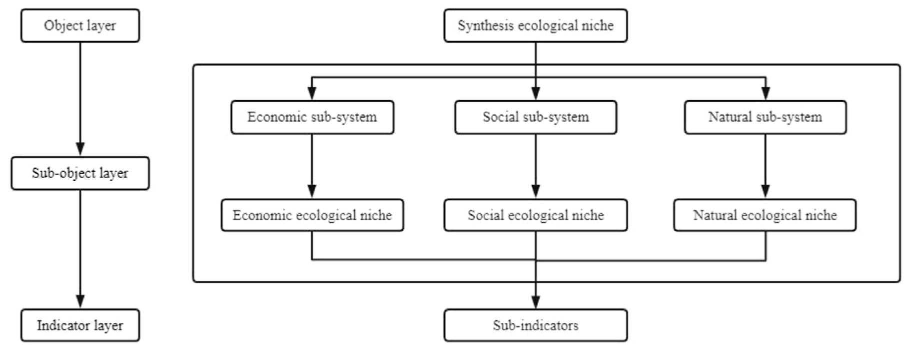

FIGURE 3 | Structure of the indicator system used to assess complex ecosystems. The ecological niche assessment indicator system comprises three levels (objectives, sub-objectives, and guidelines) with four indicators. The figure represents the indicators mentioned in **Table 1**.

Indonesia and Singapore showed high complex ecosystem indices. Additionally, other countries, such as Myanmar, Malaysia, Brunei, and China, observed significant increases in their indexes compared to the 2016 values. Overall, the complex ecosystem index increased after the BRI for all countries, except China, which represented the BRI country, thus, indicating that the BRI has an apparent policy effect. While China's complex ecosystem index in 2016 declined compared to that in 2013, theindex in 2019 increased significantly compared to that in 2016.

3.2 Analysing the Coupling Coordination of Economic-Social and Natural Ecological Niches

In summary, the coordination degree between economic-social and natural ecological niches in the CAFTA countries steadily increased, with C-values increasing from 0.686 to 0.999 and D-values increasing from 0.159 to 0.978. Moreover, coordination degrees developed to the advanced coordination stage. The pre-BRI coupling coordination level increased from Stage IV to Stage II. Further, the internal category was in a state of system balance in all years of the study period, except 2010 and 2012. After the BRI (2014–2017), the coupling coordination level was at Stage II, which was the same as that before the BRI. However, after 2018, the coupling coordination level soared from Stage II to Stage I, achieving an upward spiral. Further, both T and D values increased significantly (values close to 1) after the BRI in 2019. However, the internal category was in the natural ecological niche lag after the BRI.

As shown in **Figure 4**, the coupling coordination stage of the 11 countries significantly increased from before to after the BRI. The increase in some countries (Vietnam, Laos, Thailand, the Philippines, and Brunei) was mainly due to the increase in the level of coupling coordination and not due to changes in their internal category. The BRI changed the stage of coupling coordination from basic to advanced in Vietnam, Thailand, the Philippines, and Brunei. Such transformation was not observed in Laos, where the internal category showed a natural ecological niche lag. Laos witnessed an advanced coupling coordination before the BRI and its internal category was at the economic-social ecological niche lag level. In other countries, changes were caused due to both coupling coordination and internal categories. In Cambodia and Myanmar, the coupling coordination did not change after the BRI; however, the internal category changed from economic-social ecological niche lag to system balance. In Singapore, Indonesia, and China, the internal category changed from system balance to natural ecological niche lag after the BRI. The coupling coordination in Indonesia and China declined briefly after the BRI and subsequently, increased to the advanced coordination stage since recent years.

4 DISCUSSION

4.1 Changes in the Complex Ecosystem Index Before and After the Belt and Road Initiative

The average annual growth rate of the complex ecosystem index after the BRI was more significant than the rate before the BRI (**Figure 5**), indicating that B&R positively contributed to the overall development of the CAFTA countries. Since BRI, trade, primarily of agricultural or processed products, between the CAFTA countries has increased (Merkle and Kaupenjohann, 2000; Zhang et al., 2006; Capriolo et al., 2020). The BRI has been designed to promote shared prosperity in developing countries, and China's commitment to increasing its foreign investment in infrastructure development. The increase in the social ecological niche index benefited from the policy effects of this initiative. Most CAFTA countries are predominantly agricultural with a single under-developed industrial structure and limited resources. Labour-intensive industries are the major industries in most countries, with labour as their main competitive advantage (Liu and Xin, 2019). However, some studies showed that the BRI has broken trade barriers between the CAFTA countries and promoted the export of complementary products with geographical advantages (Huang, 2016). Compared with developed countries, the backward production technology still delayed the

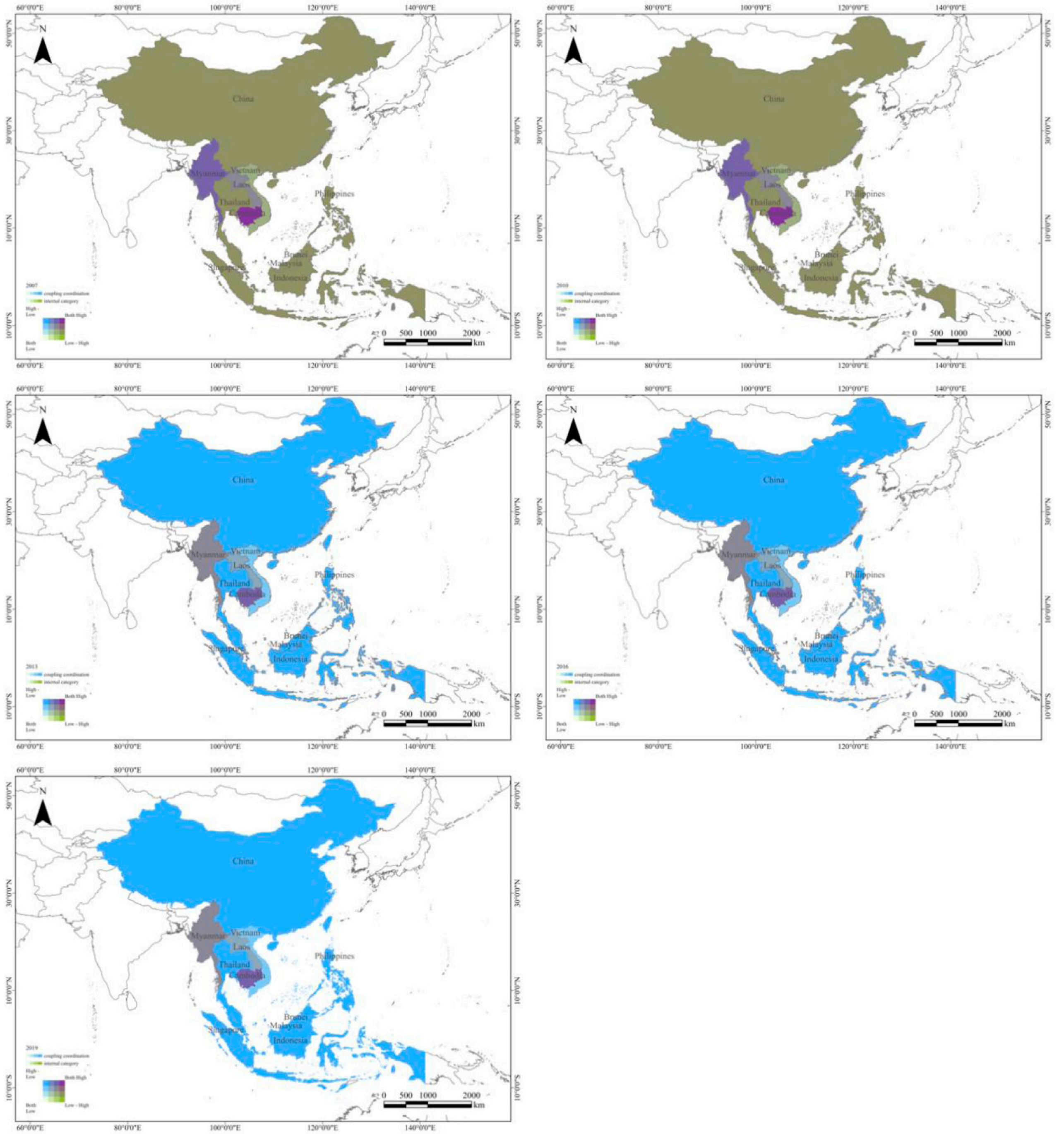

FIGURE 4 | Spatiotemporal evolution of the coupling coordination of the economic-social and natural ecological niches and their internal categories (2007–2019). The relative index values were derived from **Supplementary Appendix S2**. Internal category indicators were divided into three categories and four degrees of coupling coordination. As the binary partition coloured diagram requires that the colour categories of two metrics constitute a 4*4 size, a 0 category was constructed for the internal category, which does not have any significance.

improvement of economic ecological niche during 2007–2019. Rapid and vigorous economic development requires several resources, which consequently, increases active resource exploitation, for example, decrease in arable land area and increase in electricity consumption annually. The crude development model has also caused increasingly severe environmental pollution (Gu et al., 2018). However, the CAFTA countries have realized the importance of

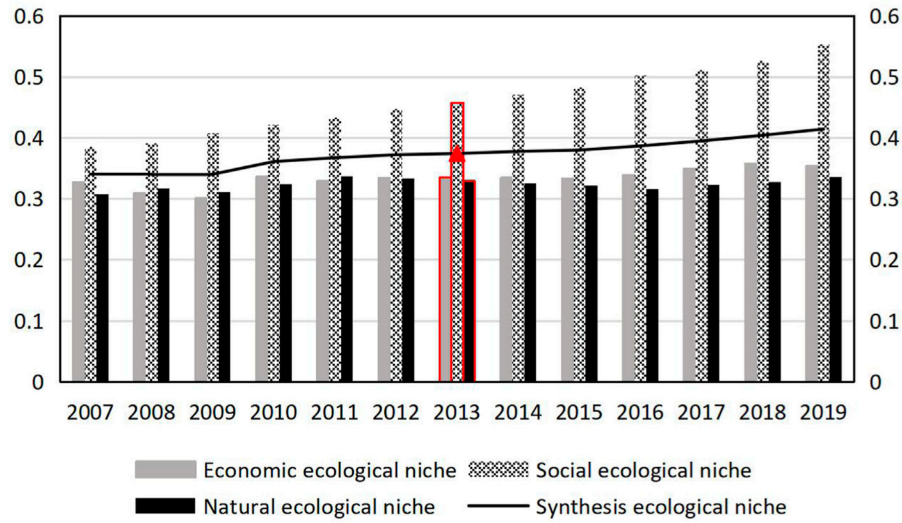

FIGURE 5 | Trends of social-economic-natural complex ecosystem in the CAFTA countries (2007–2019). The graph contains three subsystems and synthesis ecological niches, with the subsystems represented by bars and the synthesis ecological niches represented by lines.

sustainable development, changed their development patterns, and have followed a green and low-carbon development approach in recent years.

Based on the increase or decrease in the complex ecosystem index, the 11 countries were classified into three categories. Laos and China showed negative growth due to different reasons. Laos is a predominantly agricultural country with weak industrial infrastructure and negative GDP per capita growth, consequently, placing Laos in the lower ranks among the CAFTA countries regarding development. Further, as China developed the BRI, it excessively invested externally in the infrastructure development of other developing countries to achieve complementary advantages and shared prosperity. However, this investment has affected China's economic growth (Nugent and Lu, 2021; Alves and Lee, 2022; Ashraf et al., 2022). Moreover, China's economy has a crude development pattern, consumes excessive energy, and is the world's largest carbon emitter. It has led to decline in China's complex system index every year (**Supplementary Appendix S1**).

The BRI did not influence some countries, that is their complex ecosystem indices have not changed, such as Vietnam and Brunei. These countries have been economically dependent on oil production and export, and their drivers of economic growth have not changed from their original state. Although the Philippines is mainly developed in agricultural and manufacturing sectors, it is still in the 'middle-income trap' since 1982 (Quitoras et al., 2018). Therefore, the BRI did not affect the economic growth of the Philippines (**Figure 6**).

The remaining countries were positively affected by the BRI. Chinese investment in extensive infrastructure and energy projects in Myanmar since the implementation of BRI has contributed significantly to energy extraction and transportation technologies (Cox et al., 2019), thereby, demonstrating significant positive impacts. Singapore is the wealthiest country among the CAFTA countries. With rapidly increasing economy, the industrial structure of Singapore has been optimized, and its economic system has become more rational. This explains the high levels of composite complexity indices of Singapore. China has a long history of diplomatic relations with Thailand with cooperation extended in communications, railways, and tourism (Ghafoori Kharanagh et al., 2020). Consequently, Thailand's subsystem indices showed stable growth trend. Further, Malaysia has recently expanded rice cultivation to reduce its over-reliance on tropical crops (Akinyemi and Mashame, 2018). Malaysia has gradually ranked first by adjusting its industrial structure and economic development model to reduce its dependence on import and export. Cambodia and Indonesia have increased their annual complex ecosystem index by virtue of their water transport networks and BRI provides trade opportunities for the two countries (**Supplementary Appendix S1**).

4.2 Changes in the Ecosystem Coupling Coordination Before and After the Belt and Road Initiative

After the BRI, environmental conditions continued to improve, and the ecological adaptability of economic development continued to increase, therefore the coupling between the natural and economic-social niches continued to be optimized. However, the natural systems still lagged the economic-social ecological niche (**Table 3**). Specifically, during the dysfunctional development phase (pre-BRI), the CAFTA countries were dependent on agriculture, and had a simple development

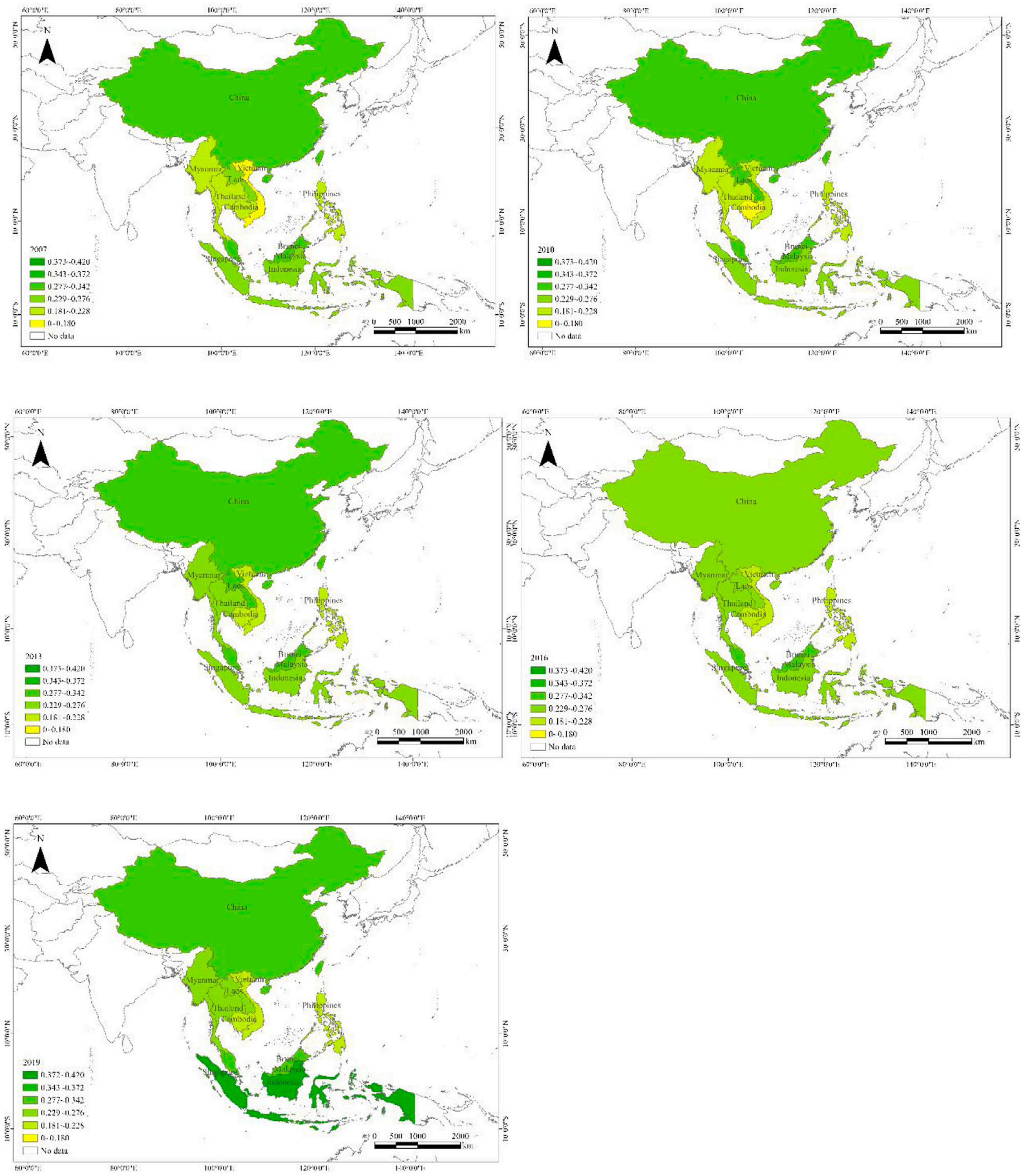

FIGURE 6 | Spatial distribution of economic-social-natural complex ecosystem in the CAFTA countries (2007–2019). The complex ecosystem index values were derived from **Supplementary Appendix Table S1**.

TABLE 3 | Coupling coordination of economic-social and natural ecological niches (2007–2019).

Year	C	T	D	Stages
2007	0.686	0.037	0.159	IV3
2008	0.342	0.166	0.238	IV3
2009	0.923	0.077	0.266	IV3
2010	0.948	0.412	0.625	II1
2011	0.85	0.648	0.742	II3
2012	0.927	0.633	0.766	II1
2013	0.974	0.577	0.75	II1
2014	0.997	0.557	0.745	II1
2015	0.997	0.518	0.719	II1
2016	0.916	0.489	0.669	II1
2017	0.981	0.645	0.796	II1
2018	0.99	0.773	0.875	I1
2019	0.999	0.958	0.978	I1

approach (Nie et al., 2022). The development advantages of their industries have not yet been fully emphasized, while the economic contribution of the tertiary sector has always been low and economic development has been slow. Further, problems in the natural environment exist, such as the depletion of natural resources, high prevalence of hazardous substances, and low arable land per capita. Breaking the contradictory pattern of economic and social development and environmental restoration is difficult, consequently, causing a weakened degree of coordinated development of the complex system. However, the coordinated degree showed a gradual improvement trend. Essentially, after executing basic coordination after the BRI, various countries started attaching importance to ecological development in ecological governance, environmental protection systems, and ecological security (Debnath et al., 2021). Consequently, the economic-social systems of CAFTA countries are developing, natural ecosystems are being restored, and complex systems are entering a new period of coordinated development. In the advanced coordination stage, the forest area of the CAFTA countries has increased, while energy consumption per unit of GDP has been gradually decreasing. In economic terms, the level of per capita income is increasing, thus, indicating that the development dynamics of regional natural systems and the benefits of economic development are simultaneously increasing. Generally, the industrial layout and operational efficiency of the economic-social system are continuously optimized (Gu et al., 2018). After the BRI, the regional natural system weakened the economic-social system, thus, showing economic-social dominance. Moreover, promoting the synchronous development of the natural system and economic-social system is a vital issue that needs attention to ensure the sustainable development of the CAFTA countries (Alves and Lee, 2022).

Vietnam, Thailand, the Philippines, and Brunei have experienced rapid economic development in recent years, with significant increases in GDP per capita and internet influence. Owing to the BRI, coupling coordination has reached advanced coordination (**Supplementary Appendix S2**). However, CO2 emissions and electricity consumption in these countries have increased significantly compared to the previous levels, some researches indicated that industrial development has increased the consumption of natural resources and minerals (Kose and Rebucci, 2005), and economic development has been achieved at the cost of the environment and resources. Consequently, internal category has been lagging behind the natural ecological niche.

Laos is a predominantly agricultural country with a weak industrial background. Although it is rich in mineral resources, the current technology stage does not allow their exploitation (Nie et al., 2022). This has resulted in a downward trend in coordination and resulted in stagnant state of an economic-social ecological niche lag. Development agreements among the CAFTA countries have encouraged Cambodia and Myanmar to traditionally follow a green development path; therefore, their economic growth model was adjusted after the BRI. Additionally, their internal categories have shifted from economic-social ecological niche lag to system balance. Some studies indicated that rapid economic development has caused environmental damages, such as environmental pollution from industrial wastewater and gaseous emissions, which does not favour sustainable economic development (Grecu et al., 2018). This in turn has caused a lag in the natural ecological position in Singapore, Indonesia, and China. Nevertheless, some scholars found that China has restructured its economy after the BRI to achieve a two-wheel-drive development comprising economic growth and ecological resilience (Alves and Lee, 2022), despite a high annual growth rate of over 9% (Huang, 2016). However, this growth was mainly driven by increased investment and the growth model was relatively crude. Blind investments and low-level repetitive construction in some industries have increased the output value but at the cost of consuming excessive resources and energy, which is not conducive to the adjustment and optimization of industrial structure (Gu et al., 2018). Moreover, such large-scale investments of resources have caused serious wastage of resources. Studies have shown that China's waste generation and energy consumption per unit of GDP are much higher than those of developed countries (Lu et al., 2020).

4.3 Implications

To promote sustainable development of the countries along the B&R, we propose several development suggestions based on the above findings. The results showed that although countries pay more attention to natural niche after BRI, the development trend of natural niche subsystem before BRI is not optimistic. Countries with fragile ecological environments should conserve and manage their environment. Additionally, while pursuing sustainable regional development, they must adhere to green growth and reduce the emission of industrial pollutants, continuously optimize the industrial layout, and limit the development of highly polluting enterprises. The economic and social ecological subsystems can improve the composite ecological niche and play a vital role in supporting regional sustainable development. In particular, the size and growth of GDP per capita, people's standards of living, and quality of life contribute extensively to the development of other aspects of the region. Lastly, investments in these areas should be increased.

5 CONCLUSION

Here, we assessed the ecological niches of the complex ecosystem and the stage of coupling coordination. In recent years, the ecological niche of a complex ecosystem has been rapidly promoted. Moreover, the economic and social ecological indices showed an upward trend. Further, the economic ecological niche showed a marginally upward trend, but the social ecological niche increased considerably. Conversely, the natural ecological niche decreased marginally, with a relatively flat trend. Furthermore, the coupling coordination between the economic-social ecological niche and the natural ecological niche of the CAFTA countries increased and advanced. Its internal category level changed from a system balance to natural ecological niche lag, indicating an inverse relation between natural resource exploitation and environmental protection. In general, these results suggested that it is imperative to improve the coordination of the natural environment to promote the quality of economic growth and social development.

The most important limitation lies in the indicators affecting the economic-social-natural complex ecological niche in the established system. Therefore, although the present study results show a development trend, they do not indicate sustainable development of each country and the impacts of the B&R construction. Future research should comprehensively examine the sustainable development status of the countries along the B&R.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://www.worldbank.org/en/home.

AUTHOR CONTRIBUTIONS

Conceptualization, ZC; methodology, YC and Wenjun Guo; resources, YC, JL and AJ; writing—original draft preparation, YC; writing—review and editing, AJ, AF, YC and WC; supervision, ZC, AJ and JL; project administration, YC and AF; funding acquisition, AJ. All authors have read and agreed to the published version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.913928/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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