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Production- and consumption-based carbon emission decoupling and decomposition of the Belt and Road countries

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The Belt and Road Initiative (BRI) provides a platform for developing countries with huge growth potentials, which may also face huge carbon emission pressure while achieving rapid economic growth. Given certain similarities in economic patterns and resource endowments, this study aims to trace carbon emission decoupling and decomposition of different countries/regions within the Belt and Road area and provide new insights into the drivers of carbon emission decoupling from both production- and consumption-based perspectives. Based on the multi-regional input-output modelling and Tapio decoupling decomposition, this study quantitatively analyzes the decoupling evolution and decomposition drivers of economic activities and carbon emissions in countries along the Belt and Road. From the results, the production-based carbon emissions of the Belt and Road countries was significantly higher than the consumption-based carbon emissions. The increasing rate in the production-based carbon emissions was also faster than the consumption-based one, with an increasing huge gap between the two sides. Regarding the spatial distribution of carbon emissions, the regions with huge amounts of carbon emissions mainly distributed in Russia, Iran, South Korea, and Saudi Arabia. When compared, the consumption-based carbon emissions of China and Russia were the highest, followed by those of the countries in Central Asia and West Asia. Compared with the production-based side, the decoupling rate of the Belt and Road countries was slower than the consumption-based one. The Belt and Road countries mainly maintained in the weak decoupling status, with the economic effect as the main driver in carbon emission growth, and the energy intensity effect as the dominated contributor in carbon emission reduction. Through exploring the decoupling and decomposition of production- and consumption-based carbon emissions within the Belt and Road countries, this study attempts to provide certain implications for the low-carbon transition and sustainable development within the countries along the Belt and Road.

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) stated that human activities lead to warming of the atmosphere, ocean, and land (IPCC, 2021), and reducing carbon emissions and achieving carbon neutrality were regarded as main strategies to prevent global climate change. Although the COVID-19 raging around the world caused a certain impact on the economic development of countries, leading to the upward trend of global carbon emissions reverse temporarily, the actions to promote low-carbon transition and strengthen international cooperation are long-term solutions to global climate change (Liu et al., 2020).

The Belt and Road Initiative (BRI) is a new platform of international cooperation proposed by China, which will usher in a new era of inclusive globalization (Liu et al., 2018). This initiative provides a significant platform to achieve mutual cooperation among developing countries and to raise the voice of international governance (Liu and Dunford, 2016). Varied types of countries participated in the Belt and Road Initiative, including emerging economies, oil exporting countries, small island countries, and the least developed countries (Chen et al., 2020). Since the proposal of the Belt and Road Initiative, the countries participated have received much attention worldwide. Meanwhile, some studies criticized that if the current carbon-intensive development model continued to be adopted in the next 20 years, the proportion of the Belt and Road countries in global carbon emissions was likely to increase (Zhang et al., 2017), which may also increase environmental pollution and climate change (Huang, 2019) and pose challenges such as political, economic, and financial risks (Ascensão et al., 2018).

In the context of economic globalization, the multi-regional input-output model has become one of the most practical methods to quantify resource use and environmental emissions at the national, regional, and provincial scales (Dolter and Victor, 2016; Song et al., 2018; Feng et al., 2021; Song et al., 2022). Globalization strengthened economic ties between countries, making the scale of international trade continue to increase as well as leading to carbon leakage (Peters and Hertwich, 2008; Peters et al., 2011; Liu et al., 2016; Lu et al., 2020). The environmental footprints of nations partnering the Belt and Road Initiative have been systematically mapped (Fang et al., 2020; Fang et al., 2021), and the embodied carbon transfer flows and carbon inequality and imbalance within the Belt and Road countries were also discussed (Han et al., 2018; Han et al., 2020; Lu et al., 2020). Note that, the IPCC Fifth Assessment Report pointed out that the consumption-based approach is an important tool for the establishment of national emission inventories (Wu et al., 2020). The responsibility for emissions caused by a country's production should also be shared by the developing and developed countries, considering the balance between producer and consumer responsibility for resources and emissions (Chen et al., 2018).

In recent years, decoupling analysis has been widely applied in the field of resource and environmental management in different industries. Among them, Wang et al. (2020) used the Tapio decoupling index method to analyze the relationship between carbon dioxide emissions and economic development in the transportation; Tang et al. (2014) used decoupling index to analyze the decoupling status of CO_2 emissions from China's tourism industry. Besides, there are also studies focusing on the decoupling relationship between economic growth, energy consumption, and carbon emissions at the regional and national scales. For example, Wang et al. (2013) analyzed the decoupling relationship between carbon emissions and economic growth in Jiangsu Province. Zhang and Da (2015) used the Tapio decoupling index to analyze the decoupling relationship between China's economic development and energy consumption. While attempts have been made to unravel the drivers of carbon emissions, different approaches were also adopted to analyze the carbon emission decomposition factors (Grand, 2016). Ren et al. (2014) used the LMDI method to analyze the influencing factors such as energy structure, industrial structure, energy intensity, economic output, and carbon emission factors. Zhang and Da (2015) found that economic growth was the main factor leading to the increase of carbon emissions, while energy intensity played a major inhibitory role in the growth of carbon emissions.

Since the Belt and Road Initiative has drawn wide attention, the Belt and Road related studies have also been conducted in different aspects. Existing studies focused on whether China's direct investment contributed to decrease carbon emission of the Belt and Road region (Su et al., 2022). The coordinated emission reduction between Chinese companies and local companies in developing countries was also tested (Shinwari et al., 2022). Besides, some studies characterized the carbon emissions and decoupling status caused by certain industry in the countries and regions (Wang et al., 2020). Previous studies also focused on embodied carbon emissions to measure the flow pattern of embodied carbon between different countries (Han et al., 2018), and the economic globalization was identified to greatly accelerate the transfer of cross-border resources and emissions embedded in international trade (Wiedmann and Lenzen, 2018).

In general, the relevant research focused on the carbon emissions of traditional Belt and Road countries and tested the driving factors of carbon emission changes in different countries, however, few studies compared the evolution of carbon emission decoupling and the decomposition of driving factors of the countries participating in the Belt and Road Initiative from the production- and consumption-based perspectives. In this context, the innovation and contribution mainly lie in the following aspects: Firstly, this study is to compare the production- and consumption-based carbon emissions of the Belt and Road countries; Secondly, this study is to depict decoupling statuses of the Belt and Road countries from both production- and consumption-based perspectives; Thirdly, this study identify the driving factors and contribution rates of carbon emission decoupling in the Belt and Road countries. From the above-mentioned perspectives, it is thus practical to scientifically analyze the decoupling and decomposition between the economic development and carbon emissions in the Belt and Road countries, therefore providing scientific support for developing countries and emerging economies along the Belt and Road to realize low-carbon transition and sustainable development.

In this context, this study measures the production- and consumption-based carbon emissions of the Belt and Road countries based on the multi-regional input-output modelling, analyzing the decoupling relationship between economic development and carbon emissions through decoupling decomposition analysis, and compares the evolution characteristics and driving factors of decoupling evolution from 1995 to 2015, providing implications for the low-carbon transition and sustainable development of countries along the Belt and Road. The rest of the study is structured as follows: Section 2 articulates the employed methodology; Section 3 demonstrates the detailed results; Section 4 discussed the major findings and policy implications; and Section 5 drawn the conclusions.

2 Methods and data sources

2.1 Carbon emission decoupling and decomposition

The Tapio decoupling can analyze the relationship between carbon emissions and economic development (Tapio, 2005) as follows:

$$\varepsilon = \frac{\%\Delta C}{\%\Delta G} = \frac{\frac{\Delta C}{C_0}}{\frac{\Delta G}{G_0}} = \Delta C \times \frac{G_0}{C_0 \times \Delta G}$$

where, ε represents decoupling index. $\%\Delta C$ and $\%\Delta G$ represent the rate of total carbon emissions and GDP changes, respectively; ΔC and ΔG represent changing values of the carbon emissions and GDP, respectively; C_0 and G_0 represent the carbon emissions and GDP in the base period, respectively.

Combining IPAT equation and LMDI decomposition (Ang, 2015), the carbon emission decomposition could be established as follows:

$$C = \sum_i (p \times g \times f_i \times e_i \times s_i)$$

where, C represents total carbon emissions; i represents the industrial sector; p represents the population scale; g represents the per capita GDP; f_i represents the industrial structure; e_i represents the energy intensity; s_i represents the carbon intensity.

Based on the additive equation of the LMDI model (Ang et al., 2003; Ang, 2005), carbon emission changes can be decomposed into five factors (Yang et al., 2016; Taka et al., 2020), in terms of the population effect (ΔC_p), economic effect (ΔC_g), industrial structure effect (ΔC_f), energy intensity effect (ΔC_e) and carbon intensity effect (ΔC_s) as follows:

$$\Delta C = \Delta C_p + \Delta C_g + \Delta C_f + \Delta C_e + \Delta C_s$$

$$\Delta C_p = \sum_i w_i \times \ln\left(\frac{p^t}{p^0}\right)$$

$$\Delta C_g = \sum_i w_i \times \ln\left(\frac{g^t}{g^0}\right)$$

$$\Delta C_f = \sum_i w_i \times \ln\left(\frac{f_i^t}{f_i^0}\right)$$

$$\Delta C_e = \sum_i w_i \times \ln\left(\frac{e_i^t}{e_i^0}\right)$$

$$\Delta C_s = \sum_i w_i \times \ln\left(\frac{s_i^t}{s_i^0}\right)$$

$$w_i = \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0}$$

2.2 Multi-regional input-output modelling

To improve the assumption of homogeneity in the input-output analysis, existing studies attempt to depict complex supply chains by constructing the multi-regional input-output (MRIO) model (Wiedmann et al., 2015). The physical balance of carbon emissions for sector i in region r is defined as follows:

$$e_i^r + \sum_{s=1}^{m} \sum_{j=1}^{n} \varepsilon_j^s z_{ji}^{sr} = \varepsilon_i^r x_i^r$$

where, e_i^r represents the direct carbon emissions of economic sector i in region r, ε_j^s represents the embodied intensity of sector j in region s, z_{ji}^{sr} represents the output from sector j in region s for intermediate input to sector i in region r, and x_i^r represents the gross output of sector i in region r. x_i^r is defined as follows:

$$x_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} f_i^{rs}$$

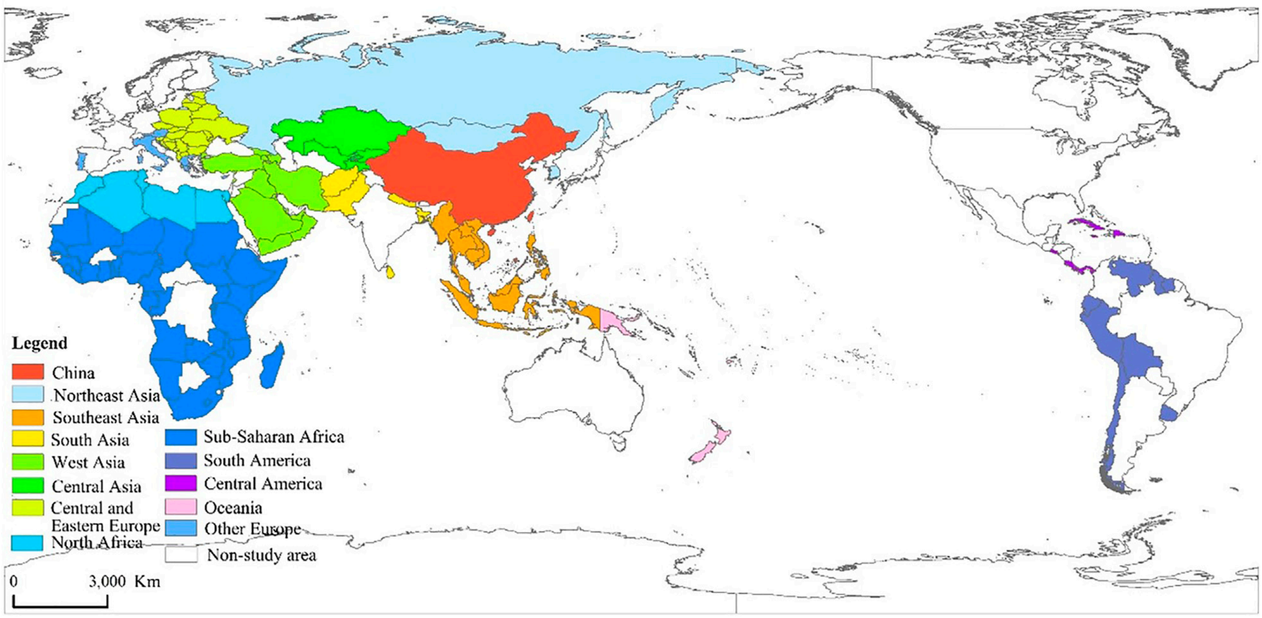


FIGURE 1
Regional classification of the Belt and Road countries.

where, f_i^{rs} represents the output from sector i in region r satisfying the final demand of sector i in region s.

Defining $E = [e_i^r]_{1\times mn}$, $\varepsilon = [\varepsilon_j^s]_{1\times mn}$, and $Z = [z_{ji}^{sr}]_{mn\times mn}$, the diagonal matrix $\hat{X} = [x_{ij}^{rs}]_{mn\times mn}$, where $r, s \in (1, 2, \ldots\ldots, m)$, $i, j \in (1, 2, \ldots\ldots, n)$, $x_{ij}^{rs} = x_i^r$ when $(i = j) \cap (r = s)$ and $x_{ij}^{rs} = 0$ when $(i \neq j) \cup (r \neq s)$, and the diagonal matrix $\hat{F} = [f_{ij}^{rs}]_{mn\times mn}$, where $r, s \in (1, 2, \ldots\ldots, m)$, $i, j \in (1, 2, \ldots\ldots, n)$, $f_{ij}^{rs} = f_i^r$ when $(i = j) \cap (r = s)$ and $f_{ij}^{rs} = 0$ when $(i \neq j) \cup (r \neq s)$, equations can be expressed in matrix form as follows:

$$E + \varepsilon Z = \varepsilon \hat{X}$$

where, ε_i^s is termed as the embodied carbon intensity of goods/services produced by sector i in country s, which implies the average amount of direct plus indirect carbon emissions to produce one unit of goods/services.

With the condition that $(\hat{X} - Z)$ is reversible, the embodied emission intensity matrix could be obtained as:

$$\tilde{E} = E\left(\hat{X} - Z\right)^{-1}$$

Based on the embodied emission intensity matrix, the direct carbon emissions (PBA) can be defined as the direct carbon emissions emitted within the territory of a country, and embodied carbon emissions (CBA) can be defined as the carbon emissions embodied in local final demand.

2.3 Study area and data sources

Overall, the Belt and Road Initiative could be regarded as a free and open platform with multiple spatial connotations (Liu and Dunford, 2016). In terms of geographical distribution, most studies applied the spatial scope of 65 countries proposed in the beginning. By the end of 2020, 138 countries and regions signed co-construction agreements with China, which were generally referred to the Belt and Road countries through signing the co-construction agreements (https://www.yidaiyilu.gov.cn/). This study divided the 138 co-constructed countries and regions into 12 sub-regions, namely Northeast Asia, Central Asia, Southeast Asia, South Asia, West Asia, Central and Eastern Europe, other European countries, North Africa, South Africa, Central America, and South America, and Oceania (see Figure 1). The data sources of Social and economic statistics including GDP, population, and industrial structure were derived from the World Bank database. Carbon emissions and energy data were derived from the International Energy Agency. The multi-regional input-output database was derived from Eora database, covering input-output data in 189 countries/economies in the world (Lenzen et al., 2013). Among them, the economic aggregate data and sub-industry economic data were adjusted to the constant price of GDP in 2010. The global maps including the national borders of countries were from the global 1:1 million basic geographic information data in the

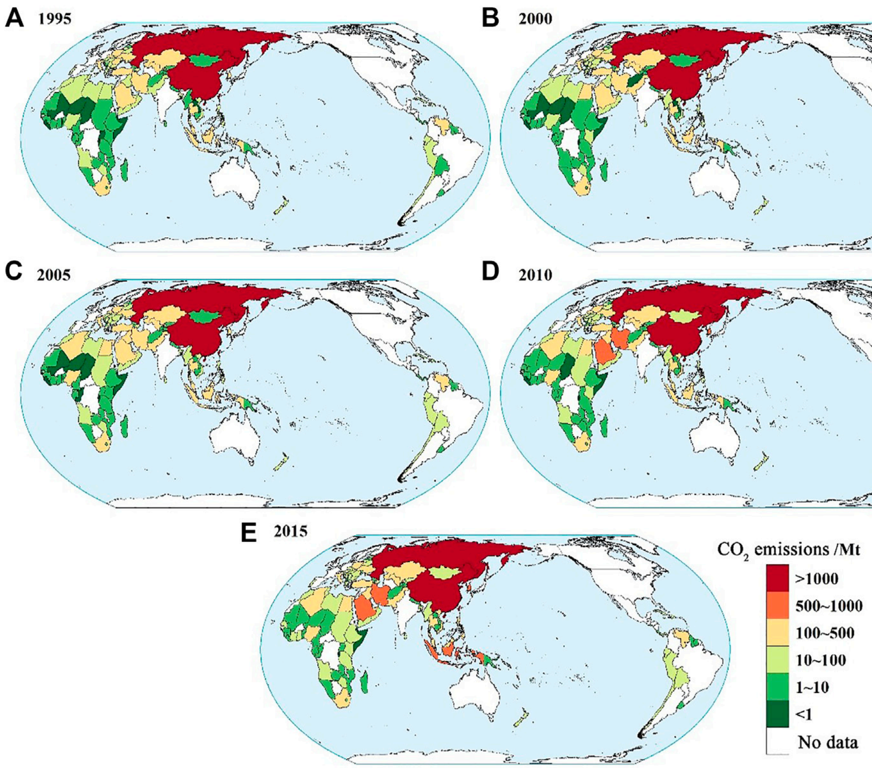


FIGURE 2
Production-based carbon emission distribution of the Belt and Road countries.

Resource and Environment Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/).

3 Results

3.1 Production- and consumption-based carbon emission distribution patterns

Overall, the carbon emissions of the Belt and Road countries including China increased from 9.89 billion tons in 1995 to 19.69 billion tons in 2015. In 2015, the Belt and Road countries accounted for 59% of the total global carbon emissions. Regarding the spatial distribution of carbon emissions (Figure 2), the carbon dioxide emissions of the Belt and Road countries were generally higher in Northeast Asia, followed by Southeast Asia, West Asia, and Central Asia. From 1995 to 2015, China, Russia, Iran, South Korea, Saudi Arabia, South Africa, Indonesia, Italy, and Poland ranked among the top, with a relatively stable distribution pattern. The carbon emissions of major economic countries such as China and Russia were far ahead (>1 billion tons) among the Belt and Road countries. Among them, China's carbon emissions increased from 3.35 billion tons in 1995 to 10.19 billion tons in 2015, with an increasing proportion from 33.90 to 51.75% in 2015. Although Russia's carbon emissions ranked in the second place, its carbon emissions remained stable around 1.60 billion tons, keeping a relatively stable status in the past 20 years. In 2015, the total carbon emissions of countries in Southeast Asia and West Asia entered the second tier (>500 million tons) behind China and Russia. Among them, the carbon emissions of countries such as Iran and Saudi Arabia in West Asia were 600 million tons, and Indonesia in Southeast Asia was about 500 million tons.

From the consumption-based perspective, the carbon emissions of countries along the Belt and Road increased from 8.57 billion tons in 1995 to 16.84 billion tons in 2015. Regarding the spatial distribution of carbon emissions (Figure 3), China, Russia, South Korea, Iran, Saudi Arabia, Indonesia, Italy, Turkey, South Africa, and Poland were at the forefront levels, with relatively balanced distribution. From the consumption-based perspective, the total carbon emissions of China and Russia in 1995 were 2.47 and 1.40 billion tons, respectively, far less than the emissions from the production-based perspective during the same period. From 2000 to 2010, China's carbon emissions from the consumption-based perspective increased rapidly. In 2010, the carbon emissions from the consumption-based reached 6.74 billion tons with an increasing ratio of about 60%. From 2010 to 2015, China's carbon

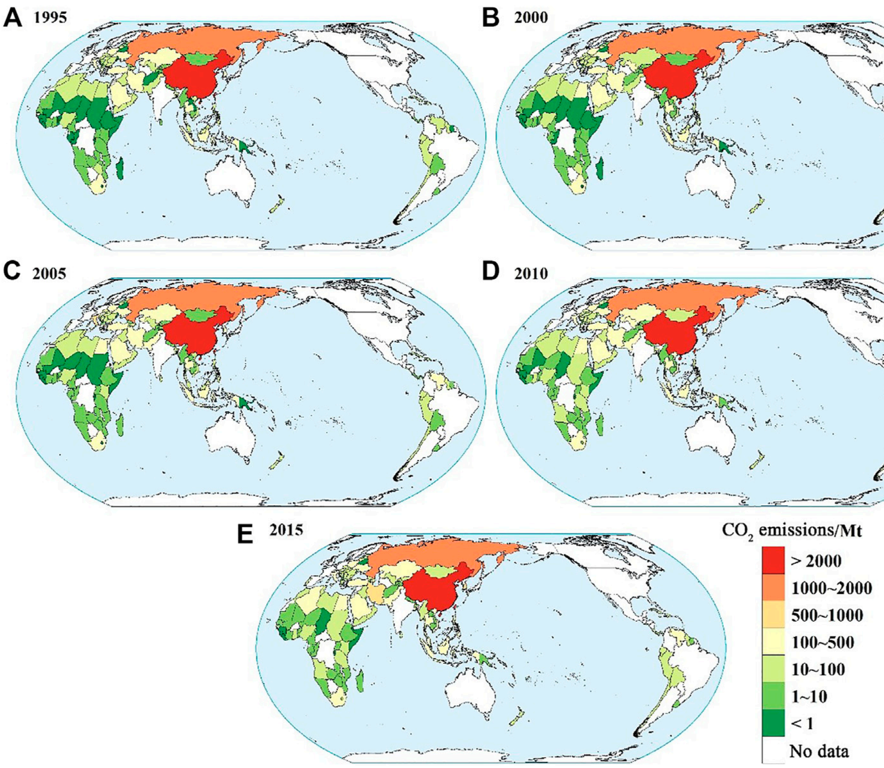


FIGURE 3
Consumption-based carbon emission distribution in the Belt and Road countries.

emissions increased to 8.13 billion tons, with a significantly dropping growth rate. Compared with the 10 billion tons of carbon emissions from the production-based perspective, there is a huge difference in China's consumption-based carbon emissions.

3.2 Production- and consumption-based carbon emission decoupling evolution

From 1995 to 2015, the Belt and Road countries were in a weak decoupling status. Except for a certain degree of expansive negative decoupling and strong negative decoupling in Southeast Asia and West and East Africa, the economic development and carbon emissions in most countries were not closely related. Almost 50% countries along the Belt and Road were dominated by strong and weak decoupling, with 16.80% in strong decoupling and 32.00% in weak decoupling.

In terms of sub-regions, Central Asia and Northeast Asia maintained in a relatively stable decoupling state. Southeast Asia and South Asia were in the same decoupling trend, showing a weak decoupling state from 2010 to 2015. West Asia maintained in a fluctuating status between expansive negative decoupling and expansive coupling. Central and Eastern Europe maintained in a strong decoupling status, only showing weak decoupling during 2000–2005. Sub-Saharan Africa turned to a stable weak decoupling status from expansive coupling, with a decreasing decoupling trend.

Figure 4 presents the decoupling statuses of carbon emissions within the Belt and Road countries from 1995 to 2015. In terms of different periods, 43.20% of the countries showed strong and weak decoupling status from 1995 to 2000, and the decoupling status of most countries in Southeast Asia was expansive negative decoupling. Compared with 1995–2000, the number of countries that achieved decoupling between economic growth and carbon emissions increased in 2000–2005, accounting for 56.80%. From 2005 to 2010, 41.60% of the countries showed strong and weak decoupling statuses. From 2010 to 2015, 52% of countries exhibited strong and weak decoupling statuses, with an increasing number of decoupling countries compared with that in 2005–2010. Cyprus, Greece, Croatia, Ukraine, and Yemen showed a recessive decoupling status during the same period. Most of the expansive negative decoupling concentrated in Eastern and Western Africa and Southeast Asia. Countries such as Iran showed a strong negative decoupling status during this period.

From the consumption-based perspective, the Belt and Road countries were dominated by weak decoupling, except

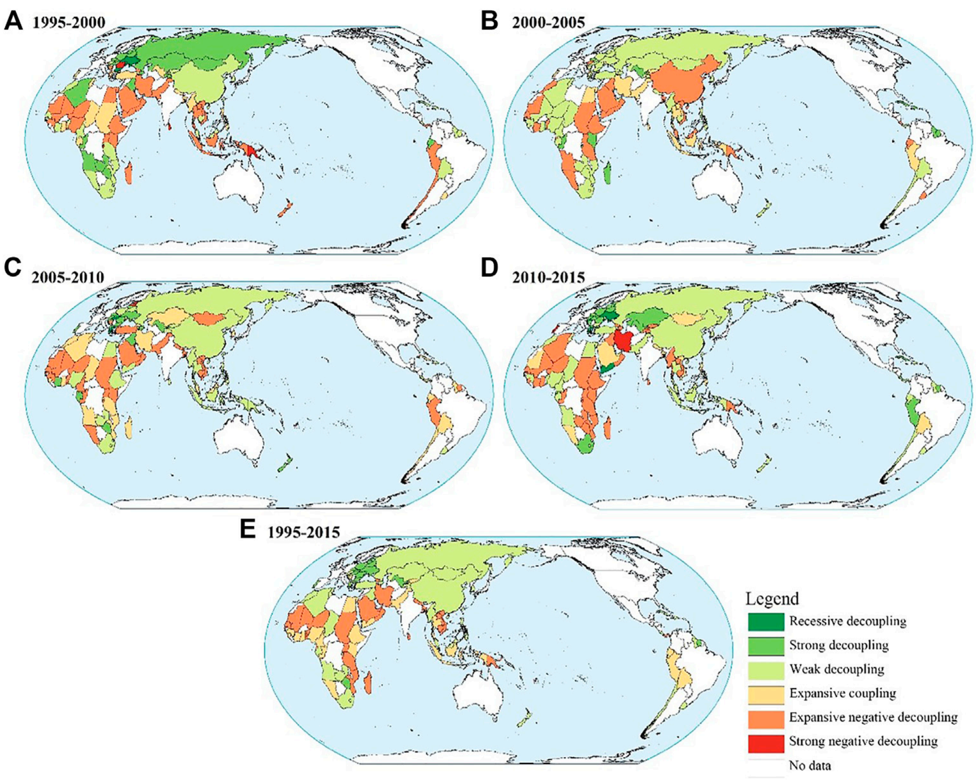


FIGURE 4
Production-based carbon emission decoupling statuses of the Belt and Road countries.

for some countries in Africa, West Asia, and Southeast Asia with the status of expansive negative decoupling. More than half (59%) of the countries were in a status of strong and weak decoupling. In terms of sub-regions, Central Asia and Northeast Asia were in a decoupling, with Central Asia tending to be strongly decoupling, while Northeast Asia dominated by weak decoupling at most of the research period. The decoupling statuses in Southeast Asia oscillated between expansive coupling and weak decoupling. South Asia maintained in the expansive coupling status, with a fluctuating decoupling trend. The Central and Eastern Europe maintained a strong decoupling status. The West Asia changed from an initial weak decoupling to an expansive negative decoupling, shifting to a weak decoupling status afterwards. The North Africa showed a weak decoupling status since 1995, expansive negative decoupling in the past 10 years, and then an increasing decoupling index in 2015. The Sub-Saharan Africa maintained a weak decoupling status, except for the expansive negative decoupling during 2000 and 2005 and the decreasing decoupling trend during 2005 and 2015.

Figure 5 presents the consumption-based carbon emission decoupling statuses from 1995 to 2015. Regarding different research periods, fewer countries decoupled carbon emissions from economic development in 2000–2005 compared with that in 1995–2000. From 1995 to 2000, 66% of the countries were in the strong and weak decoupling statuses. The Central and Eastern Europe countries such as Bulgaria, Moldova, Romania, and Ukraine maintained in a recessive decoupling status. During 2000 and 2005, the number of decoupling countries decreased significantly to 39%, with the number of strong decoupling countries falling sharply and the number of weak decoupling countries increasing. During 2005 and 2010, the number of countries with strong decoupling increased and the number of countries with weak decoupling decreased. Estonia, Italy, and Greece in Europe were in recessive decoupling, while the decoupling status in Africa was improved. After 2010, the decoupling status of the Belt and Road countries improved significantly compared with that during 2000 and 2010, with 50% of the countries showing strong and weak decoupling. Cyprus, Greece, Croatia, Italy, Portugal, Ukraine in Europe, Brunei, and Yemen in Asia maintained in recessive decoupling. The decoupling status of Africa, Southeast Asia, and South America improved significantly, while Libya and Iran maintained a strong negative decoupling status.

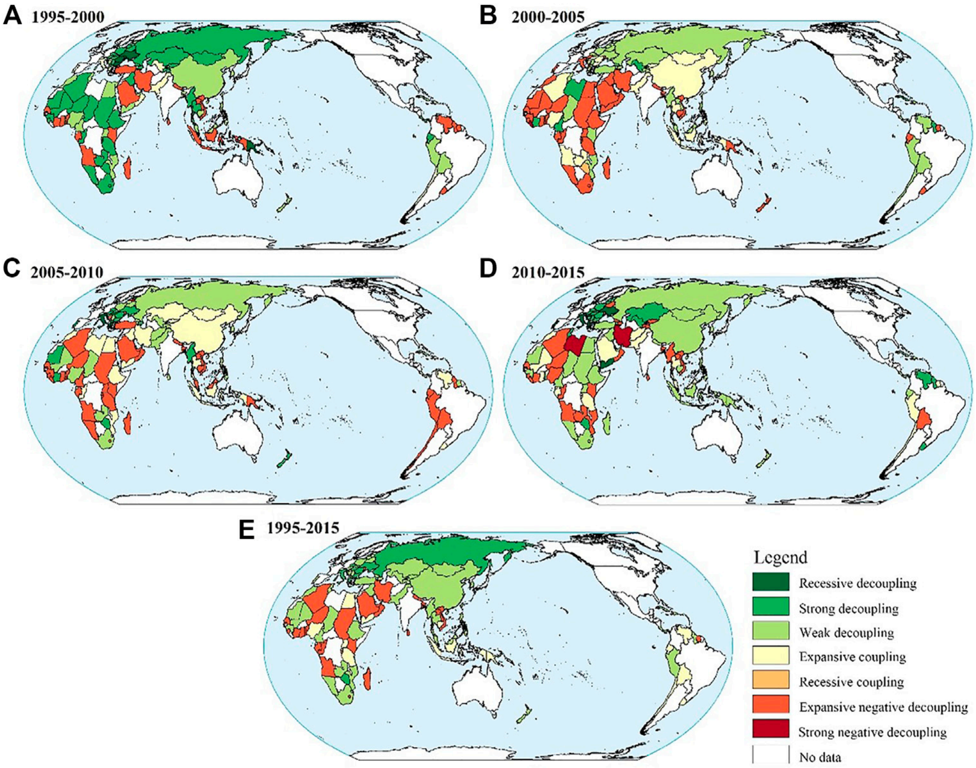


FIGURE 5
Consumption-based carbon emission decoupling statuses of the Belt and Road countries.

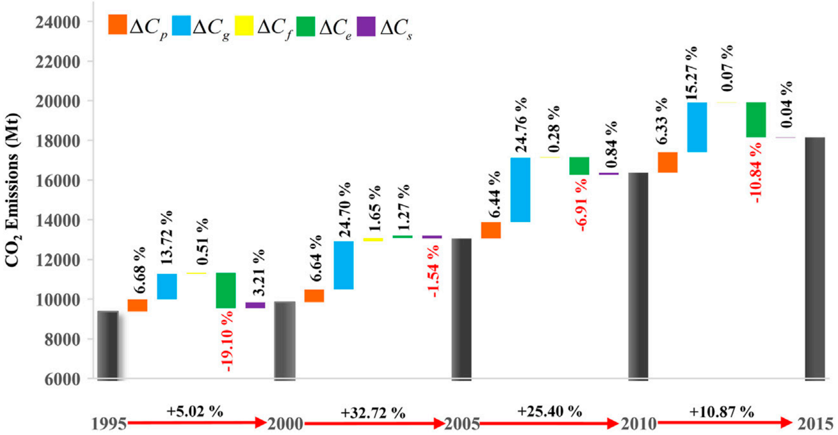


FIGURE 6
Production-based driving factors of carbon emission decoupling in the Belt and Road countries.

3.3 Driving factors of production- and consumption-based carbon emissions

Based on the decoupling decomposition analysis, the contributions of five driving factors in terms of population scale, economic level, industrial structure, energy intensity, and carbon intensity are analyzed (Figures 6, 7). The growth rate of carbon emissions in the Belt and Road countries increased rapidly during 2000–2005 and 2005–2010, especially in 2000–2005 with a growth rate of 32.72%. After 2010, the

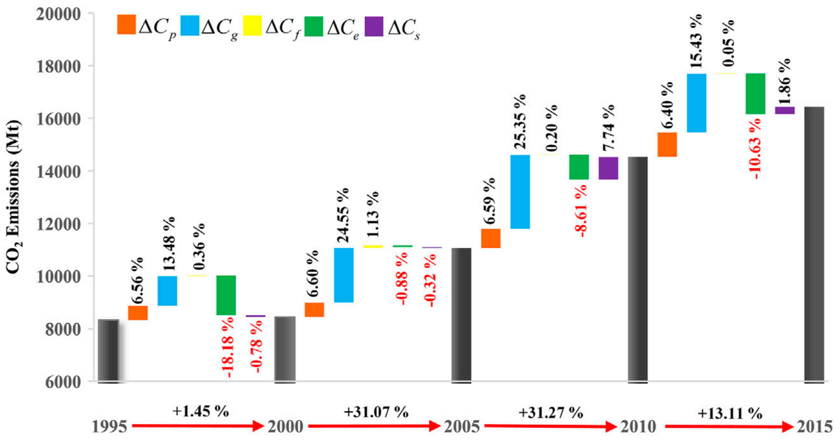


FIGURE 7
Consumption-based driving factors of carbon emission decoupling in the Belt and Road countries.

growth rate of carbon emissions dropped to 10.87% due to the financial crisis in 2008 and carbon emission reduction activities worldwide.

Among them, the population scale, the economic level, and industrial structure promoted carbon emissions in the Belt and Road countries, while the energy intensity mainly inhibited carbon emissions within this area. Regarding the influencing level, the economic level played the largest role in carbon emissions, increasing from 13.72% during 1995–2000 to 24.76% during 2005–2010. From 2010 to 2015, the contribution rate of economic level dropped to 15.27%, which was also one of the main factors promoting carbon emission reduction. The contribution of the population scale was behind that of the economic level, with the contribution rates fluctuating around 6.50%.

The energy intensity inhibited carbon emission reduction, contributing to the maximum value (−19.10%) from 1995 to 2000. Although the increase during 2000 and 2015 was lower than that from 1995 to 2000, the energy intensity still played an important role in carbon emission reduction. Except for the inhibitory effect during 2000–2005, the carbon intensity played a role in promoting carbon emissions during the rest of the research period. When compared, the effect of industrial structure had little effect on carbon emission changes.

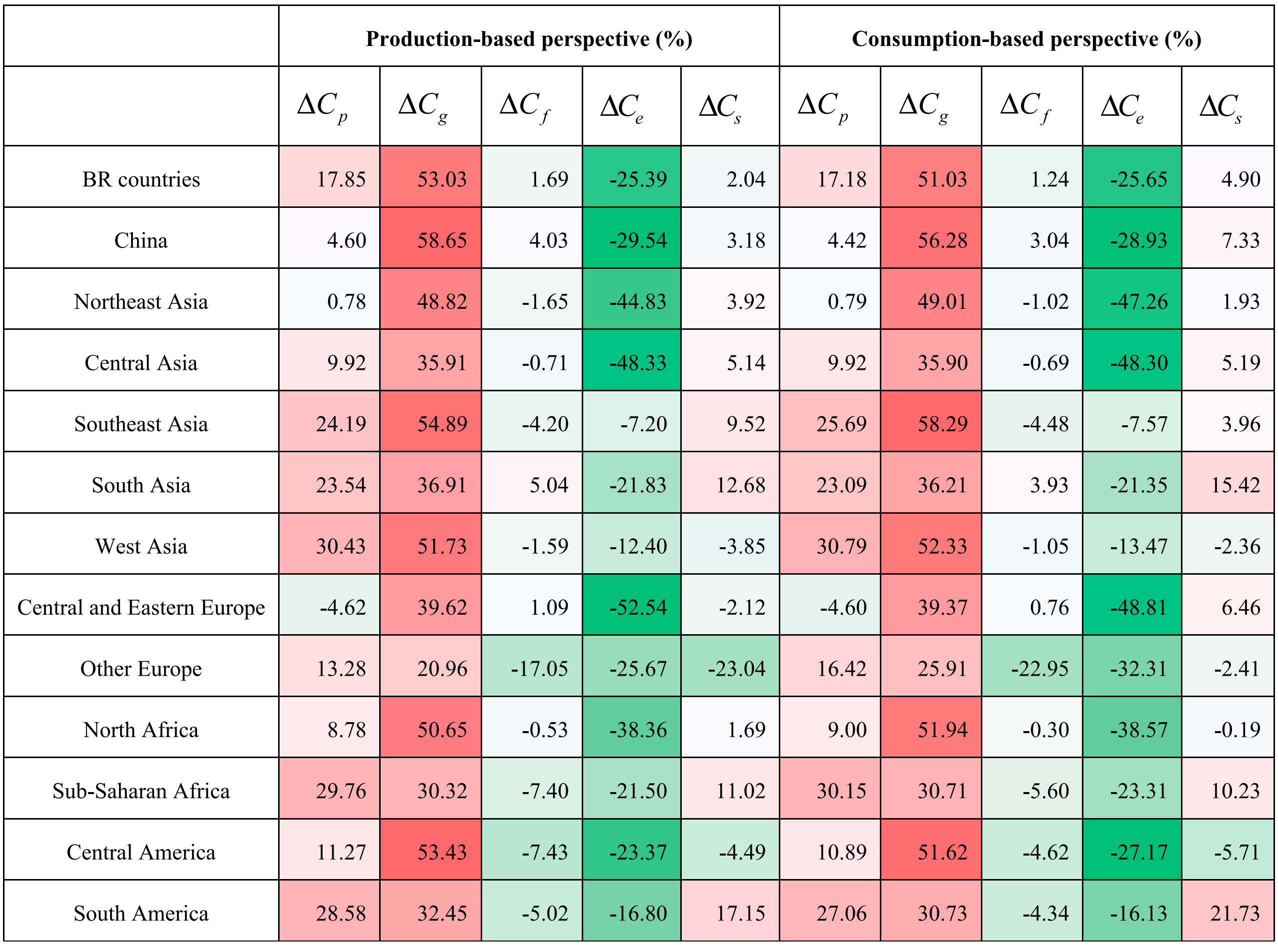
From the consumption-based perspective, the carbon emissions in the Belt and Road countries increased from 1.45% in 1995–2000 to 31.27% in 2005–2010. The economic level played a decisive role in promoting carbon emissions in the Belt and Road countries. The contribution rate reached its maximum value (25.35%) between 2005 and 2010. From 2010 to 2015, the growth rate of carbon emissions in the Belt and Road countries dropped to 13.11%, mainly due to the sharply drop of economic scale effect to 15.43% during this period. The effect of population scale was behind to that of the economic level, playing a role in promoting carbon emissions in the Belt and Road countries with a stable contribution rate of around 6.5%. Compared with the production-based carbon emissions, the growth rate of carbon emissions in the Belt and Road countries was lower than that in the production-based side during 1995 and 2005, but the opposite could be witnessed from 2005 to 2015.

The energy intensity factor played a role in suppressing carbon emissions, contributing the maximum value (−18.18%) during 1995–2000, although it only contributed −0.88% in the suppression of carbon emissions during 2000–2005. The economic level became the inhibitory effect on carbon emissions from 2010 to 2015, reaching −10.63% with a substantial reduction in carbon emission reduction. The industrial structure played a role in promoting carbon emissions, but the contribution rate was low, only contributing 1.13% in 2000–2005. The carbon intensity played an inhibitory role in carbon emissions in 1995–2000 and 2000–2005, playing a promoting role especially in 2005–2010 (7.74%).

3.4 Comparisons between production- and consumption-based carbon emissions

From the production-based perspective, the carbon emissions of the Belt and Road countries increased from 9.89 billion tons in 1995 to 19.69 billion tons in 2015. From the consumption-based perspective, the carbon emissions increased from 8.57 billion tons in 1995, increasing to 16.84 billion tons in 2015. When compared, the production-based carbon emissions of the Belt and Road

TABLE 1 Driving factors of carbon emissions in the Belt and Road countries during 1995–2015.



	Production-based perspective (%)					Consumption-based perspective (%)				
	ΔC_p	ΔC_g	ΔC_f	ΔC_e	ΔC_s	ΔC_p	ΔC_g	ΔC_f	ΔC_e	ΔC_s
BR countries	17.85	53.03	1.69	-25.39	2.04	17.18	51.03	1.24	-25.65	4.90
China	4.60	58.65	4.03	-29.54	3.18	4.42	56.28	3.04	-28.93	7.33
Northeast Asia	0.78	48.82	-1.65	-44.83	3.92	0.79	49.01	-1.02	-47.26	1.93
Central Asia	9.92	35.91	-0.71	-48.33	5.14	9.92	35.90	-0.69	-48.30	5.19
Southeast Asia	24.19	54.89	-4.20	-7.20	9.52	25.69	58.29	-4.48	-7.57	3.96
South Asia	23.54	36.91	5.04	-21.83	12.68	23.09	36.21	3.93	-21.35	15.42
West Asia	30.43	51.73	-1.59	-12.40	-3.85	30.79	52.33	-1.05	-13.47	-2.36
Central and Eastern Europe	-4.62	39.62	1.09	-52.54	-2.12	-4.60	39.37	0.76	-48.81	6.46
Other Europe	13.28	20.96	-17.05	-25.67	-23.04	16.42	25.91	-22.95	-32.31	-2.41
North Africa	8.78	50.65	-0.53	-38.36	1.69	9.00	51.94	-0.30	-38.57	-0.19
Sub-Saharan Africa	29.76	30.32	-7.40	-21.50	11.02	30.15	30.71	-5.60	-23.31	10.23
Central America	11.27	53.43	-7.43	-23.37	-4.49	10.89	51.62	-4.62	-27.17	-5.71
South America	28.58	32.45	-5.02	-16.80	17.15	27.06	30.73	-4.34	-16.13	21.73

countries were much higher than the consumption-based one, and the increasing rate in the production-based carbon emissions was also faster than the consumption-based one, with an increasing huge gap between the two sides. Taking China as an example, the production-based carbon emissions exceeded 10 billion tons, while the consumption-based carbon emissions were only about 9 billion tons, with a gap accounting for about 1/10.

Compared with the production-based side, the decoupling rate of the Belt and Road countries was slower from the consumption-based perspective. Although the decoupling status at both sides showed a weak decoupling status, the proportion of countries in the decoupling status was higher from the consumption-based perspective (59%) than that from the production-based one (49%). This was also the reason that the number of decoupling countries in the consumption-based side (66%) was much higher than that of the production-based side (43%) during 1995 and 2000. Meanwhile, the number of countries with a strong decoupling status in the production-based side was higher than that in the consumption-based side, mainly maintaining a weak decoupling status in the consumption-based side. In terms of different research periods, the proportion of countries that achieve decoupling in the production-based side was higher than that in the consumption-based side except from 1995 to 2000. However, the number of decoupled countries exceeded 50% both in the production- and consumption-based perspectives.

Note that, whether from the production- or consumption-based perspectives, the economic level was one of the main drivers in carbon emission growth, while energy intensity mainly played a role in carbon emission reduction (see Table 1). Specifically, the economic level and population scale in the Belt and Road countries were identified as the most essential driving forces in the growth of carbon emissions during 1995 and 2015, with relatively larger contribution in the production-based side than the consumption-based one. On the other hand, the energy intensity showed a restraining effect on carbon emissions from both production- and consumption-based perspectives, respectively, with a slightly larger contribution than in the consumption-based side. Regarding sub-regions, the proportion of carbon emissions in Southeast Asia, West Asia, North Africa, and Central America caused by economic level was almost 50%. The energy intensity in Central and Eastern Europe had the highest effect among all regions, especially in the production-based side. Besides, the industrial structure showed an obvious inhibitory effect especially in the developed regions such as those countries in the Europe.

4 Discussion and policy implications

Since the proposal of the Belt and Road Initiative, the countries participated have received much attention worldwide. The increase in energy consumption brought by economic development may promote carbon dioxide emissions, which makes the interactions between economic development and carbon emissions becoming a hot topic. Compared with environmental emissions, more attentions have been paid to the economic development, and the dependence of economic growth on fossil fuels led to increasing carbon dioxide emissions. To avoid economic development from being locked in carbon-intensive industries, the Belt and Road countries, especially those in least developing regions require a large number of technological transfers and financial supports.

When compared, the decoupling status of developing countries and emerging economies fluctuated greatly, with a rising processes of industrialization and economic development. Taking Southeast Asia as an example, the carbon emission decoupling statuses oscillated between expansive coupling and weak decoupling, mainly due to its position in global supply chains with a large number of low-end manufacturing industries. In contrast, developed economies tended to maintain in a stable strong decoupling status, which may because these countries effectively reduced carbon emissions within their own territory while maintaining a certain economic growth rate. The Central and Eastern Europe region maintained in a strong decoupling status, since most of the regions were developed economies with advanced technology and optimized industries.

Regarding different factors, economic development was considered as primary factors contributing to the growth of carbon emissions. Especially, Safi et al. (2021) found that economic growth will promote the growth of carbon emissions in the short and long term especially in seven emerging economies including China and India. Ridzuan et al. (2020) revealed an inverted U-shaped relationship between the economic growth and carbon emissions. Shakib et al. (2022) proposed that energy consumption showed a promoting effect on carbon emissions, and dependence on fossil energy was an important factor leading to the growth of carbon emissions in countries along the Belt and Road.

When compared, the economic level had a larger impact on carbon emissions compared with other factors, and the population scale also showed a certain impact on the growth of carbon emissions. The per capita GDP was also identified as one of the major driving factors for the increase in carbon emissions (Pani and Mukhopadhyay, 2011; Yao et al., 2015). For countries in Southeast Asia, South Asia, West Asia, and Southern Africa, most maintained a relatively high growth rate with a huge population base. The expansion of the population size aggravated the increase of energy requirements, thus further driving the growth of carbon emissions. Especially in the ASEAN region, the GDP is projected to grow steadily with the lowest growth rate of 2.39% in Brunei and the highest growth rate of 7.87% in Myanmar (Paltsev et al., 2018). It is predicted that the energy consumption of the ASEAN region will grow by about 80% while electricity will grow by about 115% from 2015 to 2030 (Paltsev et al., 2018), which means there remain huge potentials for the region to achieve continued economic growth and raise living standards with increasing energy consumption.

From the decomposition analysis, energy intensity has also been identified as the major driver behind the decrease in CO_2 emissions (Pani and Mukhopadhyay, 2013). Among them, Northeast Asia and Central Asia maintained a stable weak decoupling status during 1995 and 2015, with a relatively larger impact of the energy intensity factor. The energy intensity effect in the Central and Eastern Europe even exceeded the proportion of economic growth, which played a decisive role in carbon emission reduction and an essential contributor to achieve strong decoupling. According to the ASEAN Plan of Action for Energy Cooperation 2016–2025, the ASEAN committed to reducing its energy intensity by 20% from the 2005 levels by 2020 and by 30% by 2025 and to increase renewable energy to 23% of its energy mix by 2025, which means substantial efforts will be made to facilitate policy implementation, diversify the energy mix, and cut emissions by guaranteeing the broader incorporation of renewable energy and greater energy efficiency.

In 2015, the Paris Agreement proposed to control the temperature increase in the 21st century within 2°C as the benchmark, and to control the temperature increase to within 1.5°C as a long-term development goal. In March 2015, the National Development and Reform Commission, the Ministry of Foreign Affairs, and the Ministry of Commerce jointly issued the Vision and Actions to Promote the Joint Construction of the Silk Road Economic Belt and the 21st Century Maritime Silk Road, which clearly pointed out to strengthen the green and low-carbon infrastructure of infrastructure and strengthen cooperation in ecological environment, biodiversity, and climate change, and jointly build a green Silk Road. In April 2017, the Ministry of Environmental Protection, the Ministry of Foreign Affairs, the National Development and Reform Commission, and the Ministry of Commerce jointly issued the Guiding Opinions on Promoting the Construction of Green Belt and Road, emphasizing the green and low-carbon construction of the Belt and Road. Based on the derived results in this study, some practical policy implications and suggestions for countries along the Belt and Road to achieve low-carbon transition are as follows:

1) Reshaping energy structures from traditional to renewables. The energy intensity was identified as an essential driver to achieve carbon emission decoupling. A substantial reduction in energy intensity can represent an upgrade in the energy structures, resulting in a reduction in energy consumption per unit of economic value. Although the transition pathways varied by region, some policies include cutting fossil fuel subsidies, expanding renewable energy investment, encouraging renewable energy development, promoting electrification rate, and continuing financial support for low-carbon technologies would be practical.
2) Promoting coordinated and balanced development patterns. Most of the Belt and Road countries were developing and underdeveloped countries, facing huge carbon emission pressure while requiring economic development. Countries such as Southeast Asia and South Asia actively undertook related industries in developed countries to ensure their economic development, and it is practical to actively adopt green technologies and encouraging renewable energy generation through international cooperation.
3) Formulating decarbonization pathways that suit national conditions. Although the Belt and Road countries shared certain similarities in economic patterns and resource endowments, there are still significant differences in the changing trends and driving factors of carbon emissions across countries. Targeted policies thus should be considered in line with the country's economic development levels and carbon decoupling statuses.
4) Strengthening international cooperation between countries. Developed countries with advanced technologies and abundant funds are suggested to take more responsibility to transfer advanced low-carbon technologies to developing and less developed countries. The carbon emission reduction experience from China may also provide experiences and implications for countries along the Belt and Road to achieve low-carbon transition and sustainable development.

5 Conclusion

Based on the multi-regional input-output modelling and the decoupling decomposition analysis, this study analyzes the decoupling statuses between carbon emissions and economic development in countries along the Belt and Road from 1995 to 2015 and identifies the contribution rates of five factors including population scale, economic level, industrial structure, energy intensity, and carbon intensity from production- and consumption-based perspectives, attempting to provide quantitative implications for the Belt and Road countries to achieve low-carbon transition and sustainable development. From 1995 to 2015, the production-based carbon emissions of the Belt and Road countries increased from 9.89 billion tons in 1995 to 19.69 billion tons in 2015, while the consumption-based carbon emissions increased from 8.57 billion tons to 16.84 billion tons, which was significantly lower than the carbon emissions in the production-based side. The Belt and Road countries were generally in a well decoupling status during the research period in both production- and consumption-based side. From the production-based perspective, almost 50% countries along the Belt and Road maintained in strong and weak decoupling statuses, while more than half (59%) of the countries were in a status of strong and weak decoupling in the consumption-based side. In terms of different periods except for 1995–2010, the proportion of decoupling countries in the consumption-based side was lower than that in the production-based one. Regarding driving factors, the economic level was the most essential force to drive the growth of carbon emissions, while the energy intensity factor was the most important contributor in carbon emission reduction. Especially in weak and strong decoupling areas where the decoupling status tended to be stable, the contribution rate of the energy intensity factor in the carbon emission reduction was comparable to that of the economic level. Meanwhile, the impact of the population scale on carbon emissions was also essential, especially in the developing countries and emerging economies. Since there was significant disparity in the driving factors of production- and consumption-based carbon emission changes in the Belt and Road countries, it is necessary to explore the carbon emission decoupling and decomposition of the Belt and Road countries, enlightening significance for the low-carbon transition and jointly constructing the Green Silk Roads.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JZ data curation, methodology, visualization, writing—original draft; MH conceptualization, methodology, writing—reviewing and editing.

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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.

Publisher's note

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